electricity volume-three

HARRY MILEAF • EDITOR-IN-CHIEF

A-C CIRCUITS □ ALTERNATING CURRENT □ A-C WAVEFORMS □ RESISTIVE CIRCUITS □ INDUCTORS □ INDUCTIVE CIRCUITS □ TRANSFORMERS □ CAPACITORS □ CAPACITIVE CIRCUITS

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Electricity One—Seven Series

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preface

This volume is one of a series designed specifically to teach electricity. The series is logically organized to fit the learning process. Each volume covers a given area of knowledge, which in itself is complete, but also prepares the student for the ensuing volumes. Within each volume, the topics are taught in incremental steps and each topic treatment prepares the student for the next topic. Only *one* discrete topic or concept is examined on a page, and *each* page carries an illustration that graphically depicts the topic being covered. As a result of this treatment, neither the text nor the illustrations are relied on solely as a teaching medium for any given topic. Both are given for *every* topic, so that the illustrations not only complement but reinforce the text. In addition, to further aid the student in retaining what he has learned, the important points are summarized in text form on the illustration. This unique treatment allows the book to be used as a convenient review text. Color is used not for decorative purposes, but to accent important points and make the illustrations meaningful.

In keeping with good teaching practice, all technical terms are defined at their point of introduction so that the student can proceed with confidence. And, to facilitate matters for both the student and the teacher, key words for each topic are made conspicuous by the use of italics. Major points covered in prior topics are often reiterated in later topics for purposes of retention. This allows not only the smooth transition from topic to topic, but the reinforcement of prior knowledge just before the declining point of one's memory curve. At the end of each group of topics comprising a lesson, a summary of the facts is given, together with an appropriate set of review questions, so that the student himself can determine how well he is learning as he proceeds through the book.

Much of the credit for the development of this series belongs to various members of the excellent team of authors, editors, and technical consultants assembled by the publisher. Special acknowledgment of the contributions of the following individuals is most appropriate: Frank T. Egan, Jack Greenfield, and Warren W. Yates, principal contributors; Peter J. Zurita, Steven Barbash, Solomon Flam, and A. Victor Schwarz, of the publisher's staff; Paul J. Barotta, Director of the Union Technical Institute; Albert J. Marcarelli, Technical Director of the Connecticut School of Electronics; Howard Bierman, Editor of *Electronic Design;* E. E. Grazda, Editorial Director of *Electronic Design;* and Irving Lopatin, Editorial Director of the Hayden Book Companies.

HARRY MILEAF
Editor-in-Chief

contents

Alternating Current 3-1

What is Alternating Current? ☐ Is Alternating Current Useful? ☐ Why is Alternating Current Used? ☐ Electric Power Transmission ☐ Transmission Power Loss ☐ Transmission of A-C Power ☐ Other Characteristics of AC ☐ The A-C Power Source ☐ A Simple A-C Generator

Summary and Review Questions 3-10

A-C Waveforms 3-11

Angular Motion ☐ A-C Waveforms ☐ A-C vs. D-C Waveforms ☐ The Sine Wave ☐ Generation of a Sine Wave ☐ Symmetry of A-C Waveforms ☐ The Square Wave ☐ Generation of a Square Wave ☐ The Sawtooth Wave ☐ Fluctuating DC ☐ The A-C Component

Summary and Review Questions 3-22

A-C Characteristics 3-23

Frequency ☐ Wavelength ☐ Phase ☐ Phase Difference ☐ Other A-C Terms ☐ Values of A-C Voltage and Current ☐ Average Values ☐ Effective Values ☐ Converting Values

Summary and Review Questions 3-32

Resistive A-C Circuits 3-33

Resistive A-C Circuits ☐ Current and Voltage ☐ Phase Relationships ☐ Power ☐ Eddy Currents and Skin Effect ☐ Solved Problems

Summary and Review Questions 3-41

Nonresistive A-C Circuits 3-42

Effects of Electromagnetism 3-43

The Magnetic Field Around a Conductor ☐ Induced EMF ☐ Factors Determining Induced EMF ☐ The Magnetic Field Created by an Alternating Current ☐ Self-Induction ☐ Magnitude of Self-Induced EMF ☐ Polarity of Self-Induced EMF ☐ Self-Induction From an Energy Standpoint ☐ Effect of Conductor Shape on Self-Induction

Summary and Review Questions 3-53

Inductance 3-54

Inductance ☐ Inductors ☐ Factors Determining Inductance ☐ Inductance Values and CEMF

Inductive D-C Circuits 3-58

Inductive D-C Circuits ☐ Inductive Time Constant ☐ Rising and Falling Currents ☐ Effect of Increasing or Decreasing Inductance

Inductive A-C Circuits 3-62

Inductive A-C Circuits ☐ A-C Voltage and Current Relationships ☐ Inductive Reactance ☐ Series and Parallel Inductors ☐ Solved Problems

Summary and Review Questions 3-70

Mutual Inductance 3-71

Mutual Induction ☐ Mutual Inductance

Transformers 3-73

The Transformer ☐ Transformer Operation With Open Secondary ☐ Voltage and Current ☐ Transformer Operation With Loaded Secondary ☐ Voltage and Current ☐ Effect of Load on Phases ☐ Primary and Secondary Power ☐ Turns Ratio vs. Voltage and Current ☐ Multiple-Secondary Transformers

Summary and Review Questions 3-84

Transformer Types 3-85

Types of Transformers ☐ Iron-Core and Air-Core Transformers ☐ The Autotransformer ☐ The Adjustable Transformer

Transformer Losses 3-90

Transformer Losses ☐ Copper Loss and Leakage ☐ Hysteresis Loss ☐ Hysteresis Loop ☐ Eddy Current Loss ☐ Saturation Loss

Summary and Review Questions 3-96

RL Circuits 3-97

Capacitance and the Capacitor 3-98

Capacitance and the Capacitor ☐ Charging a Capacitor ☐ The Electric Field ☐ Charging a Capacitor in a D-C Circuit ☐ Discharging a Capacitor ☐ Discharging a Capacitor in a D-C Circuit ☐ Unit of Capacitance ☐ Capacitive Time Constant

Summary and Review Questions 3-108

Capacitance and the Capacitor (Cont.) 3-109

What Controls Capacitance Values ☐ Effect of Plate Surface

Area □ Effect of Plate Separation □ Effect of the Dielectric □ Dielectric Constant and Strength

Capacitive D-C Circuits 3-115

Summary and Review Questions 3-116

Capacitive A-C Circuits 3-117

Capacitive A-C Circuits □ Voltage Relationships □ Voltage and Current Relationships □ Effect of Frequency on Capacitor Current □ Effect of Capacitance on Capacitor Current □ Capacitive Reactance □ Leakage Resistance □ Series Capacitors □ Parallel Capacitors □ Solved Problems

Capacitive Fluctuating D-C Circuits 3-131

Summary and Review Questions 3-133

Power Factor 3-134

Capacitor Types 3-135

Types of Capacitors □ The Electrolytic Capacitor

Capacitor Color Codes 3-139

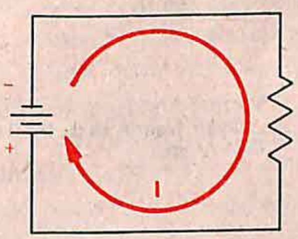
RC Circuits 3-141

Summary and Review Questions 3-142

what is alternating current?

In Volume 1, electric current was described as the movement of free electrons in a conductor that is connected between a difference of potential. The current flows as long as the difference of potential is present. If the polarity of the potential difference never changes, the current always flows in *one direction* and is called *direct*, or d-c *current*. D-c current and d-c circuits were described in detail in Volume 2.

There is a type of electric current that does *not* always flow in the same direction. Instead, it *alternates*, flowing first in one direction, and then reversing and flowing in the other. This type of current is called *alternating*, or a-c *current*.

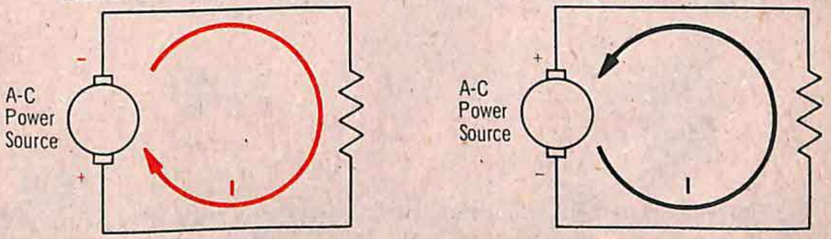


D-C CIRCUIT

Unlike d-c current, which always flows in the same direction, a-c current periodically changes its direction

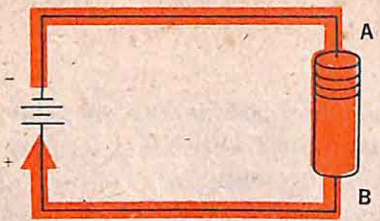
A-c current flows in one direction, then . . .

It reverses and flows in the other direction

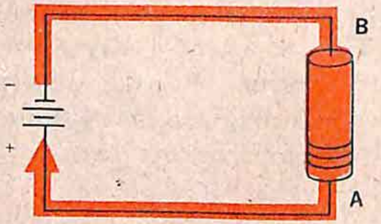


A-C CIRCUIT

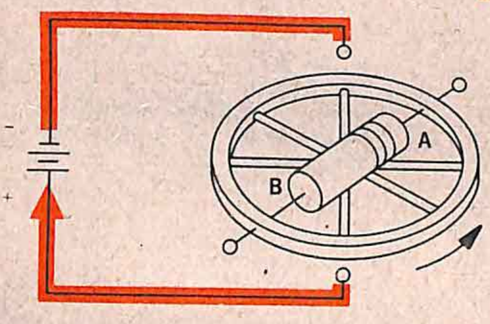
Since, in any circuit, current flows from the negative terminal of the power source to the positive terminal, it is obvious that for a-c current to flow, the polarity of the power source must alternate, or change direction. Power sources that do this are called *a-c power sources*. Circuits that use a-c power sources, and that therefore have a-c current flowing in them, are called *a-c circuits*. Similarly, the power consumed in an a-c circuit is *a-c power*.



Current always flows through the resistor from A to B



Current always flows through the resistor from B to A



Current first flows through the resistor from A to B, then from B to A, etc.

Heat is developed in this resistor regardless of the direction in which the current flows. Alternating current, therefore, has the same effect on the resistor as does direct current

is alternating current useful?

When you are first introduced to alternating current you may wonder whether it can be put to any *practical* use. Since it reverses in direction, it may seem that anything it would do while flowing in one direction, it would undo when it reversed and flowed in the opposite direction. This is not the case, however.

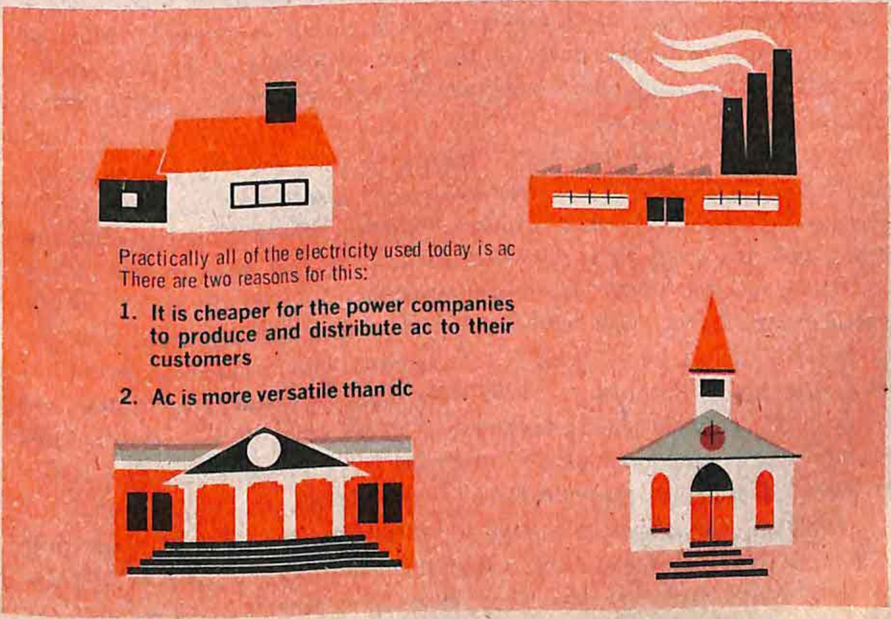
In a circuit, the flowing electrons themselves do not do any useful work. It is the *effects* they have on the loads they flow through that are important. And these effects are the same regardless of the direction of the current. For example, when current flows through a resistance, heat is *always* produced. It makes no difference whether the current is always in one direction, always in the opposite direction, or sometimes in one direction and sometimes in the other.

why is alternating current used?

Direct current was the first source of electric power to be widely used. But as more became known about the characteristics of alternating current, it gradually replaced dc as the primary source of electric power in use. Today about 90 percent of all the electric power consumed through the world is ac. In the United States, this percentage is even higher. There are some sections in our older cities where the electric power is still dc. These sections, though, are gradually being changed to ac.

What are the reasons for this changeover? Why should nine times as much a-c power be used as dc? Basically, there are two reasons for it. One is that, for the most part, ac can do everything that dc can, and in addition, can be *sent* from the point where it is produced to the point where it will be used *more easily* and *cheaply* than dc can. The second reason for the widespread use of ac is the fact that it can do certain things and be used for certain applications for which dc is unsuited.

You should not get the impression that dc will soon be obsolete and all electricity used will be ac. There are many applications, particularly inside of electrical equipment, where only dc can perform the desired function.

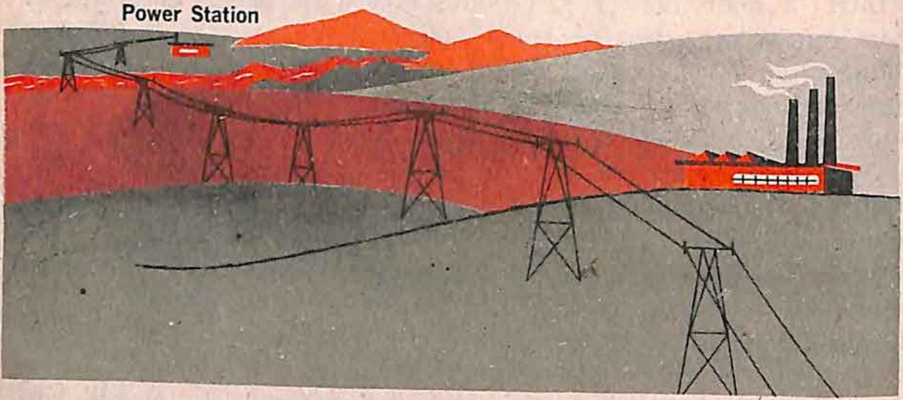


Practically all of the electricity used today is ac
There are two reasons for this:

1. **It is cheaper for the power companies to produce and distribute ac to their customers**
2. **Ac is more versatile than dc**

Electric power stations cannot be built near every home, factory, and farm. They must usually be located near the available sources of natural energy, such as large rivers

The electric power the stations produce, then, has to be sent long distances to the users. Large power losses result if dc is sent over long distances. With ac, these losses are greatly reduced



electric power transmission

In an ideal electric circuit, *all* of the energy produced by the power source would be converted by the load into some *useful* form, such as light or heat. In practice, though, it is impossible to build an ideal circuit. Some of the energy from the power source is used in the circuit interconnecting wires, and some is also used within the power source itself. This use of energy outside of the load represents *wasted energy* or *wasted power*, and so should be kept as small as possible. Most of this power *loss* is in the form of the *heat* generated when the circuit current flows through the resistance of the wiring and the internal resistance of the source.

You probably remember from Volume 2 that these resistances are usually very low, and the power losses are, therefore, very small. An important exception to this, though, is when the wiring between the source and the load is *very long*, such as is the case in the transmission of electric power from the power stations to the users. These electric power lines, with which you are undoubtedly familiar, can be hundreds of miles long. And even large-diameter, copper wire, which has a very low resistance for 1000 feet, has a considerable amount of total resistance if hundreds of miles of it are used. Silver wire, which has the lowest resistance of all, could be used, but it would not lower the total resistance significantly, and would cost too much.

How, then, can large amounts of electric power be sent over long distances without large losses along the transmission lines? With dc, this cannot be done. But with ac, it is relatively easy.

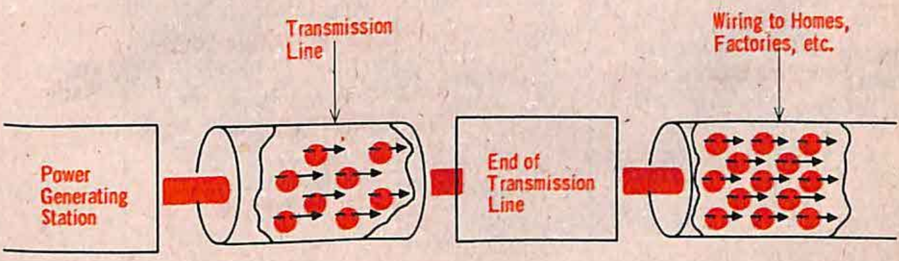
transmission power loss

In the transmission of electric power, a portion of the power is converted into heat along the length of the transmission line. From Volume 2, you should recall that this heat loss is *directly proportional* to the resistance and to the *square* of the current. This is shown by the formula for *power loss:*

$$P = I^2R$$

The heat, or power loss (P) can thus be reduced by lowering either the current (I) carried by the transmission line, the resistance (R) of the wire, or both. However, the resistance has much less effect on the power loss than the current because the current is "squared."

In the transmission of a-c power, the current carried by the transmission line is relatively small



At the end of the transmission line, this small current is converted to the large currents required by the users of power. This keeps the I^2R (power) losses low in the transmission lines

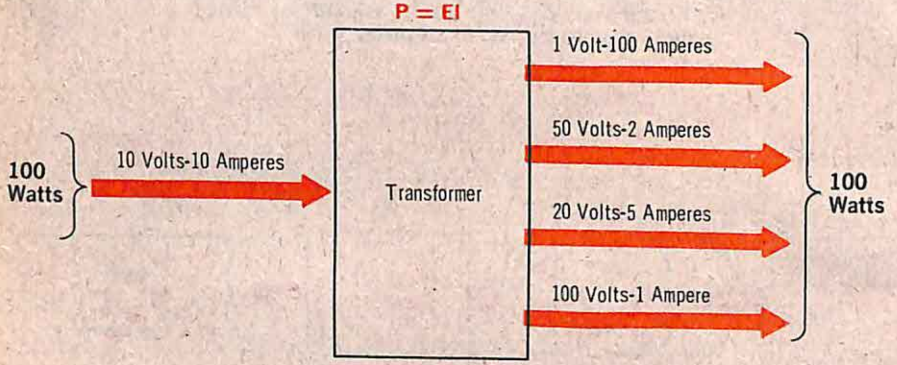
If the resistance was doubled, the power loss would double; but if the current is doubled, the power loss would be quadrupled. So the best way to reduce the power losses is to *lower* the *current*. But large currents are required by the users of the electric power at the end of the transmission line. What is needed, then, is a method of having low currents in the transmission line, but large currents available at the end of the line. This is possible with a-c power. Relatively low currents are sent along the transmission lines, and when they reach the point where they are to be used, they are converted to high currents.

transmission of a-c power

It may seem unreasonable that electric power can be transmitted with *low current* in the transmission line, and yet at the end of the line, the power is available with a *high current*. To understand this, you should recall the voltage–current equation for electric power:

$$P = EI$$

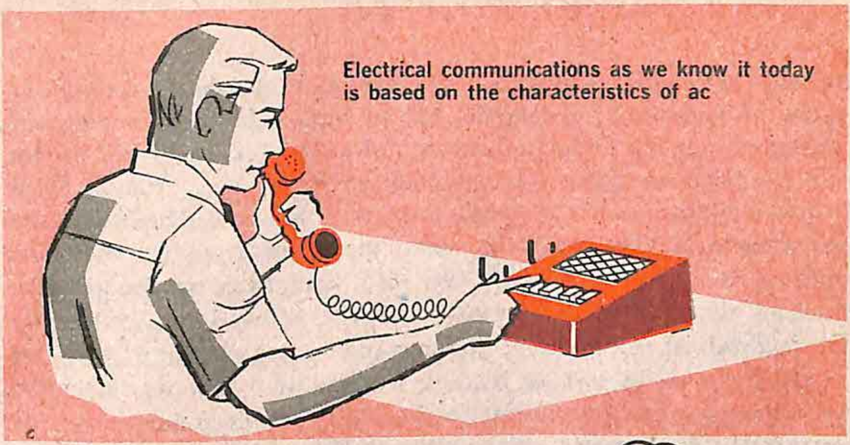
You can see from this equation that the *identical* power (P) can be produced by *many combinations* of currents (I) and voltages (E). For example, you can get 1000 watts of power from a voltage of 100 volts and a current of 10 amperes, from a voltage of 200 volts and a current of 5 amperes, or from a voltage of 1000 volts and a current of 1 ampere.



A-c power can be converted to various combinations of voltage and current. The value of the power after the conversion is the same as its value before conversion, since P = EI

A million watts of power can, therefore, be sent over a transmission line in many ways. It could be sent at a voltage of 1000 volts, in which case the current would then be 1000 amperes, and the power loss along the line would be very high. Or it could be sent at a voltage of 100,000 volts with a current of only 10 amperes, and the power loss would be much less. At the end of the transmission line, the transmitted combination of voltage and current can then be converted to any other combination of voltage and current that produces a total of a million watts.

The devices used to convert a-c power from one combination of voltage and current and another are called *transformers*. They will be examined later in this volume.



Electrical communications as we know it today is based on the characteristics of ac

other characteristics of ac

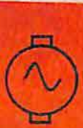
The fact that it can be sent over long transmission lines cheaply and easily is not the only advantage that ac has over dc. Ac has other characteristics that dc does not have which make it ideally suited for certain uses. One of these characteristics is the fact that it *varies* in value, or magnitude. It does not rise immediately to a maximum value and stay at that value until the circuit is opened, as dc does. This changing level is similar to the way the level of sound waves in the air change. Thus, in the field of electrical communications, ac is used to reproduce and transmit sound electrically.

Another important characteristic of ac is the fact that electrical energy *radiates* from any circuit in which alternating current is flowing. This characteristic is the basis of radio communications, and is widely used in the field of electronics.

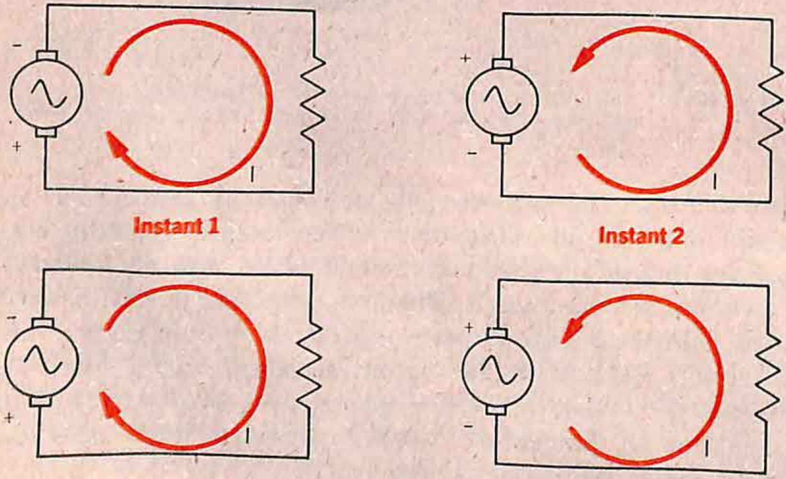
the a-c power source

The purpose of any electric power source is to provide a *voltage*, or difference of potential, between its output terminals, and to maintain this voltage when the circuit is closed and *current* flows. In d-c power sources, the polarity of the output voltage *never* changes. One terminal is *always negative*, and the other is *always positive*. Therefore, the circuit current is always in the same direction; from the negative terminal of the source, through the load, and back to the positive terminal of the source. A-c sources, on the other hand, *constantly change polarity*. At any instant, one terminal is negative and the other one is positive. At some later instant, the terminal that was negative becomes positive, and the one that was positive becomes negative. This reversal in polarity is continuous, and each time it happens, the circuit current changes direction, since it must always flow from the negative to the positive terminal.

A-c power sources are called *a-c generators*, or *alternators*.



THIS IS THE SYMBOL FOR AN A-C POWER SOURCE



Instant 1

Instant 2

Instant 3

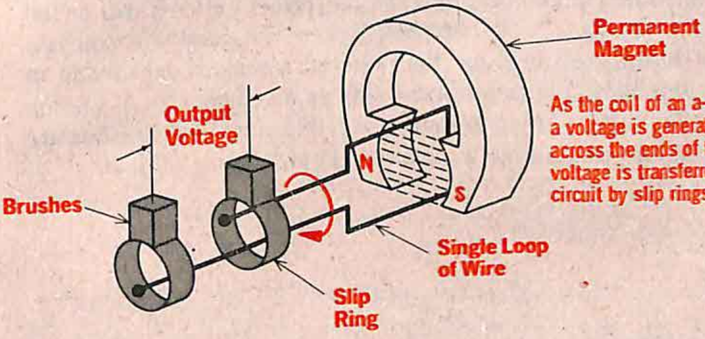
Instant 4

The polarity of a-c power sources changes continuously. Each time the polarity reverses, the circuit current also changes direction

a simple a-c generator

A-c generators combine physical motion and magnetism to produce an a-c voltage. You learned from Volume 1 that if a conductor is moved through a magnetic field in such a way that it passes through the flux lines, a force is applied to the free electrons in the conductor, causing them to move. Since the force thus causes current flow, it can be considered an emf, or a voltage. This is the basic principle on which a-c generators work.

The simplest type of a-c generator is shown. It consists of a single *loop* of wire, which is placed between the poles of a permanent magnet and made to *rotate*. As the loop rotates, it passes through, or *cuts*, the magnetic lines of force, and a voltage is developed. In a practical generator, this loop is actually a series of loops contained on a *rotor* or an *armature*.



As the coil of an a-c generator rotates, a voltage is generated that appears across the ends of the coil. This voltage is transferred to an external circuit by slip rings and brushes

The voltage produced exists between the two ends of the loop. *Slip rings* and *brushes* are used to apply the voltage to an external circuit. The slip rings are smooth rings made of conducting material. One ring is connected to each end of the loop, and both rings rotate as the loop rotates. The output voltage of the generator thus exists between the two slip rings. The brushes are in contact with the slip rings, one brush for each ring. The brushes do not move, but stay in contact with the slip rings by sliding along their surface as they rotate. In this way, the output voltage of the generator is between the brushes and can easily be applied to a circuit.

You can see from the description that something must turn the loop for the generator to work. This "something" could be flowing water, a gasoline engine, steam created by burning coal, or even steam produced by a nuclear reactor.

A-c generators are covered in detail in Volume 6.

summary

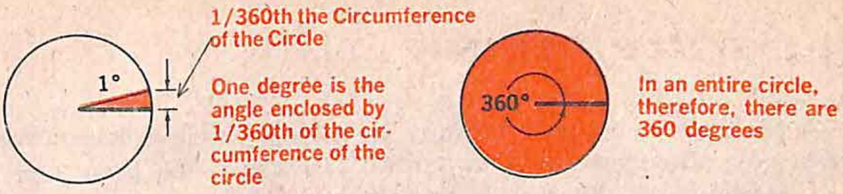
☐ Alternating current flows first in one direction, and then reverses and flows in the other. ☐ A-c power sources cause a-c current to flow. ☐ Circuits that use a-c power sources are called a-c circuits, and the power consumed by them is a-c power. ☐ Ninety percent of all electric power consumed throughout the world is ac.

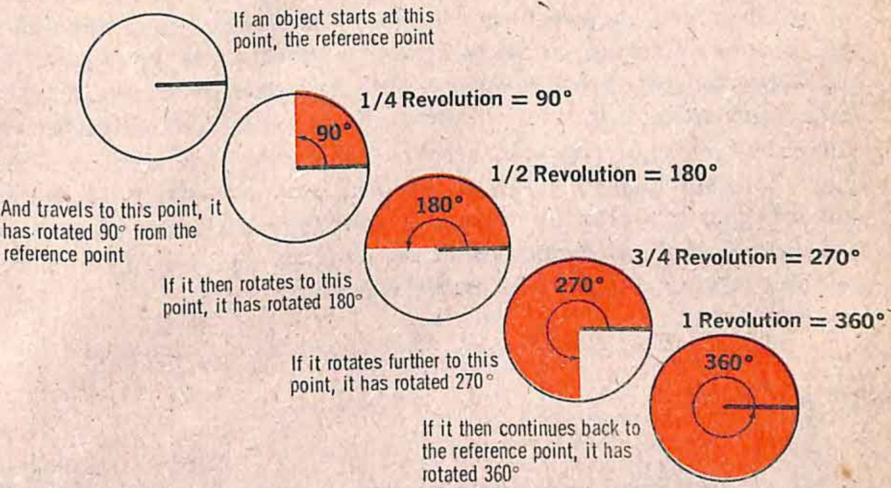
☐ There are two basic reasons why ac is used: it can be transmitted more easily and cheaply than can dc; and it can do certain things and be used for certain applications for which dc is unsuited. ☐ Heat generated in transmission lines is wasted power. ☐ The transmission of a-c power at a relatively low current keeps power losses to a minimum. ☐ The same power level can be produced by many combinations of voltage and current.

☐ Electrical energy radiates from any circuit in which alternating current flows. This is the basis of radio communications. ☐ A-c power sources are called a-c generators or alternators. ☐ The simplest type of a-c generator consists of a single loop of wire placed between the poles of a magnet and made to rotate. The cutting of magnetic lines of force develops a voltage. ☐ A rotating series of loops is called a rotor, or an armature. ☐ Slip rings and brushes are used to apply the output voltage from a generator to an external circuit.

review questions

1. What is *a-c current*? *D-c current*?
2. Is d-c electric power still used in the United States?
3. What is meant by *power losses*?
4. How can power losses be minimized?
5. What is the effect on the power loss if the resistance of a transmission line is doubled?
6. What is the effect on the power loss if the current through a transmission line is doubled
7. What device is used to convert a-c power from one combination of voltage and current to another? Why is it used?
8. What are a-c power sources called?
9. What are *slip rings* and *brushes*?
10. Which would produce the greater power loss: the transmission of power at 100 volts and a current of 10 amperes, or at 200 volts and 5 amperes?


1/360th the Circumference of the Circle
1°
One degree is the angle enclosed by 1/360th of the circumference of the circle
360°
In an entire circle, therefore, there are 360 degrees


If an object starts at this point, the reference point
1/4 Revolution = 90°
90°
And travels to this point, it has rotated 90° from the reference point
1/2 Revolution = 180°
180°
If it then rotates to this point, it has rotated 180°
3/4 Revolution = 270°
270°
If it rotates further to this point, it has rotated 270°
1 Revolution = 360°
360°
If it then continues back to the reference point, it has rotated 360°

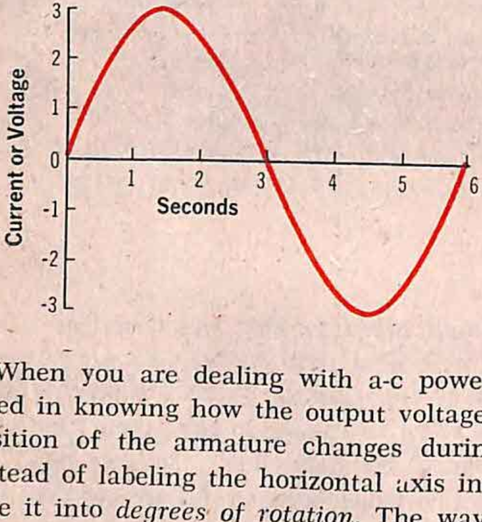
angular motion

The loop of wire in the simple generator that was described on page 3-9 rotated within the magnetic field. And, as you know, rotation is movement in a *circle*, such as the turning of an airplane propeller. You will find later that it is often necessary to talk about the voltage that results from each position of the loop of wire as it rotates. To do this, you have to understand *angular motion* and the way it is expressed.

Angular motion is motion in a circle. It is usually described by dividing the circumference of a circle into 360 equal lengths. If lines are drawn from the ends of any one of these lengths to the center of the circle, the distance between the lines is called *1 degree*. Since this can be done for each of the 360 equal lengths, there are *360 degrees* in the *circle*. A line from the circumference of the circle to the center is called a *radius*. And so the distance between any two radii of a circle is measured in *degrees*. This distance is always measured in a counterclockwise direction from one radius to the other. In practical use, one radius corresponds to the body or object that is rotating. The other radius is a *reference point* from which the position of the first radius is measured.

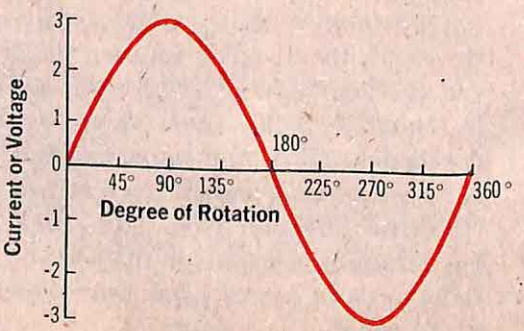
a-c waveforms

Very often, it is useful to know how a current or voltage *changes* with time. The easiest way to do this, and a way that gives a picture representation of the current or voltage, is to construct a *waveform* on graph paper. A waveform shows the *magnitude* and *direction* of the current or voltage at every instant of *time*. To make a waveform, you label the two axes as shown. One axis, usually the vertical one, is the *current* or *voltage axis*, and is divided into suitable divisions of current or voltage. The other axis is usually the *time axis*, and is divided into suitable divisions of time, such as seconds. With the axes labeled, you then plot the current or voltage at each unit of time as a dot on the graph. And when all of the dots are connected by a continuous line, the resulting figure is the waveform.



Waveforms can be plotted for either current or voltage. They show how the current or voltage varies with time

When you are dealing with a-c power sources, you may be interested in knowing how the output voltage of a generator varies as the position of the armature changes during its rotation. In this case, instead of labeling the horizontal axis in units of time, you would divide it into *degrees of rotation*. The waveshape would then show the magnitude and polarity of the voltage for each position of the armature.

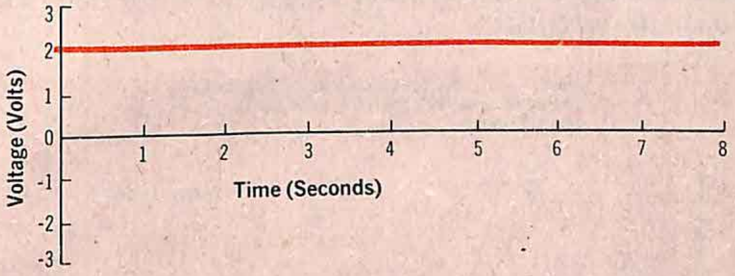


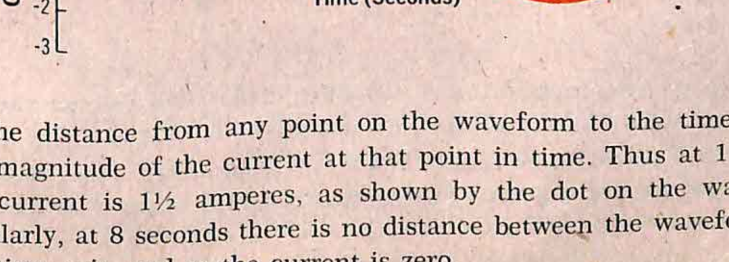
For a-c power sources, waveforms can also show how the output voltage varies with the position of the generator armature

a-c vs. d-c waveforms

The polarity and magnitude of a d-c current or voltage never change. Therefore, the waveform of a 2-volt d-c voltage would be a straight line.

An a-c current or voltage changes in both magnitude and polarity. This can be seen from the waveform of an a-c current. Where the waveform is above the zero current line, the current is flowing in one direction, which is called the positive direction in this case. Where the waveform is below the zero current line, as shown in color, the current has reversed and is flowing in the opposite direction. You can see that the current represented by the waveform first flowed in one direction, then reversed and flowed in the other direction, and started to reverse again, all within 8 seconds time.

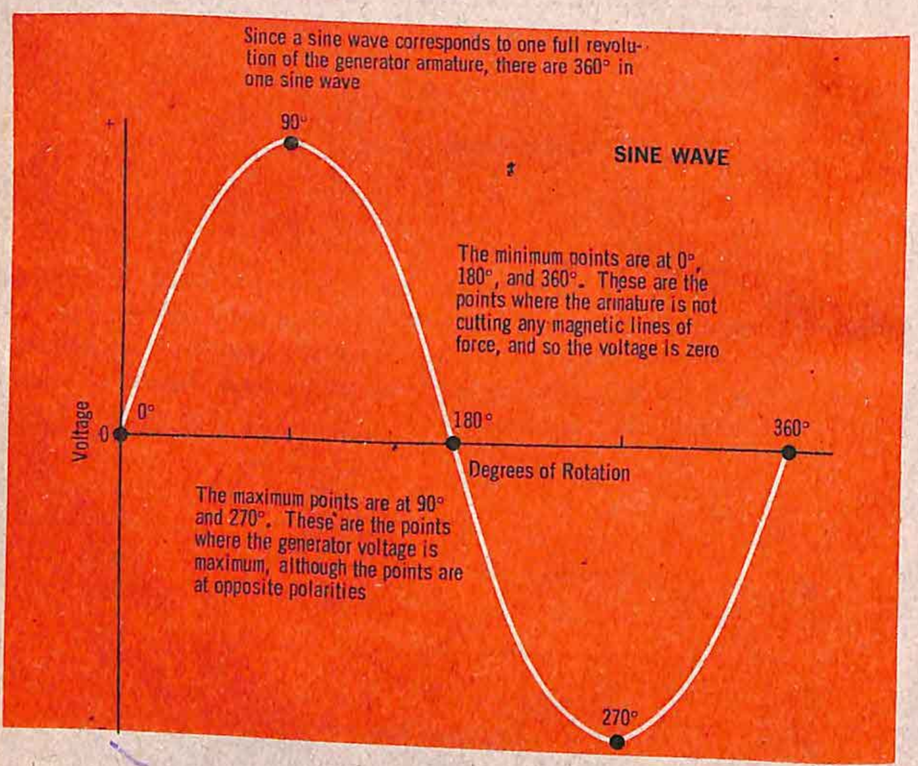




The distance from any point on the waveform to the time axis is the magnitude of the current at that point in time. Thus at 1 second, the current is 1½ amperes, as shown by the dot on the waveform. Similarly, at 8 seconds there is no distance between the waveform and the time axis, and so the current is zero.

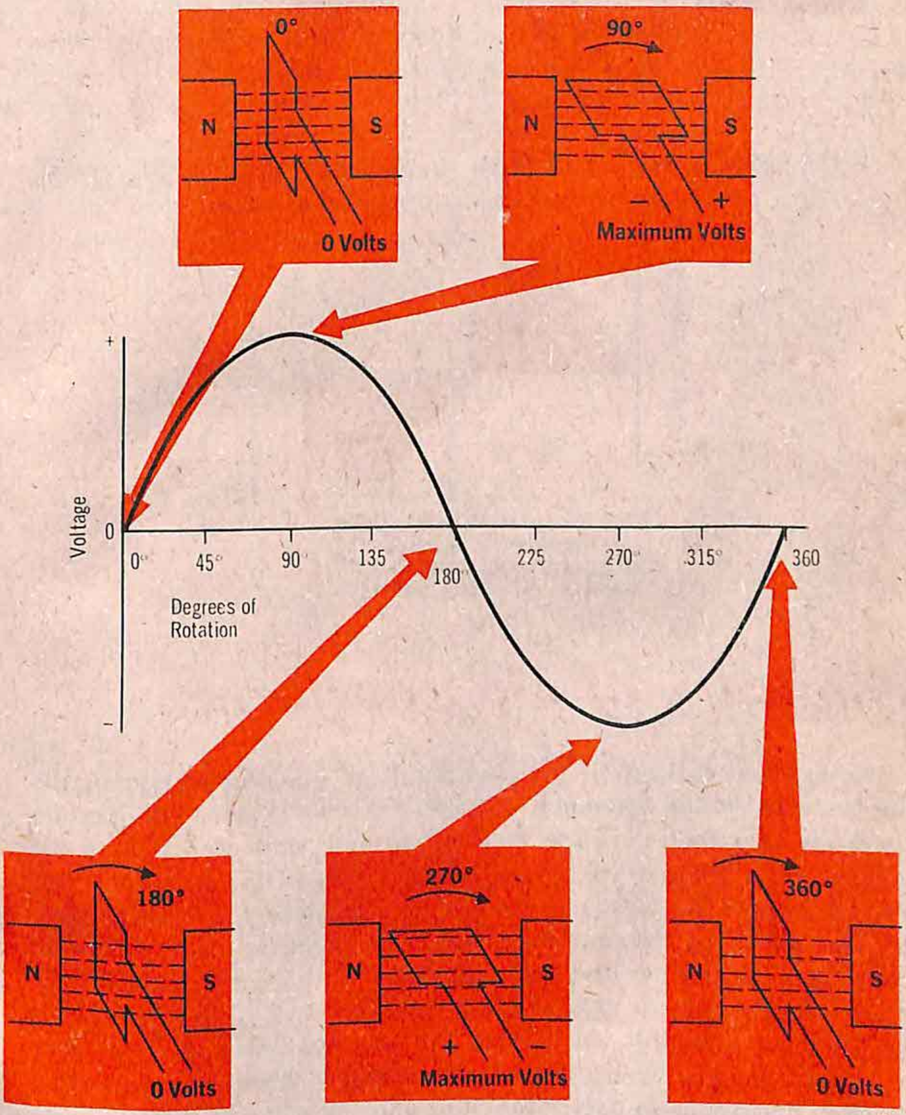
the sine wave

The voltage produced by the simple a-c generator described previously has a characteristic waveform that is important throughout a-c circuit theory. This waveform describes the output voltage of the generator during *one full revolution* of the armature. The voltage starts at *zero*, when the armature is not cutting any magnetic lines of force. As the armature turns, the voltage increases from zero to a *maximum* value in one direction. It then decreases until it reaches *zero* again. At zero, the voltage reverses polarity, and increases until it reaches a *maximum* at this opposite polarity. It then decreases until it reaches *zero* again. At this point, the generator armature has completed one *full revolution.*



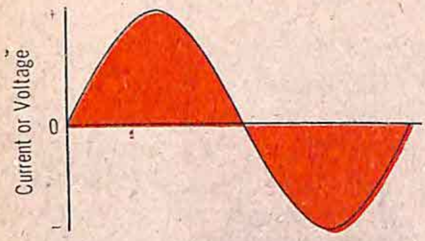
For every revolution that the armature makes, the voltage varies in this same way. The waveform that describes this variation in voltage for one full revolution of the armature is called a *sine wave*. It gets its name from the fact that the voltage generated at any point in the armature's travel is proportional to the sine of the angle between the magnetic field and the direction of motion of the armature.

generation of a sine wave

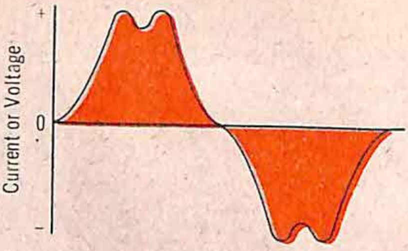


As the generator armature rotates, the magnitude and polarity of the voltage produced follows the pattern of the sine wave

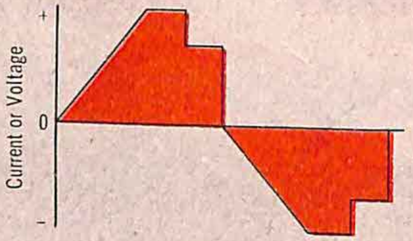
A-C Waveforms Are Symmetrical About the Horizontal Axis



This is an a-c sine wave



This is an a-c waveform that varies continuously in magnitude but in a different manner than a sine wave



This is an a-c waveform that does not vary continuously in magnitude. The magnitude does not change where the waveform is a horizontal straight line

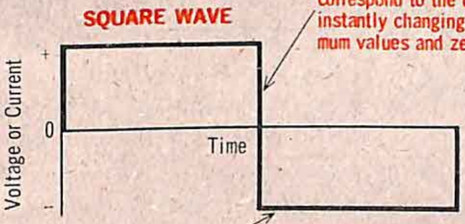
symmetry of a-c waveforms

Perhaps you noticed on the previous page that the portion of the sine wave *below* the horizontal axis has the *same* shape as the *portion* above the axis. Both have the same height and width, and vary in the same way. In other words, if the negative part of the waveform was pivoted around the axis and brought up alongside the positive part, the two halves of the waveform would be identical. This *symmetry* of the positive and negative portions of the waveform is characteristic of a-c voltages and currents. If the waveform is not symmetrical about the horizontal axis, it is not *pure* ac. We can thus define an a-c current or voltage as one which periodically changes direction, and which varies in magnitude in one direction exactly the same as it does in the other direction.

In working with ac, you will become familiar with other waveforms besides the sine wave. Two of the most common, and two with which you should become thoroughly familiar, are the *square wave* and the *sawtooth wave*.

the square wave

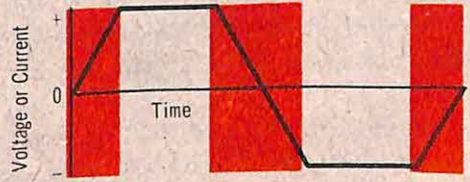
A very common type of waveform in which the current or voltage does not vary in magnitude continuously is called the *square wave*. In a square wave, the current or voltage increases *instantly* from *zero* to some *maximum* value. It then does not vary, but *stays* at this maximum value for a period of time. After this period of time, the current or voltage does three things *instantly:* (1) it *decreases* to zero, (2) it *reverses* direction, and (3) it *increases* to its maximum value in this opposite direction. It stays at this negative maximum value for a time, and then *decreases instantly* to zero. The waveform is thus made up of a series of *straight lines*, as shown.



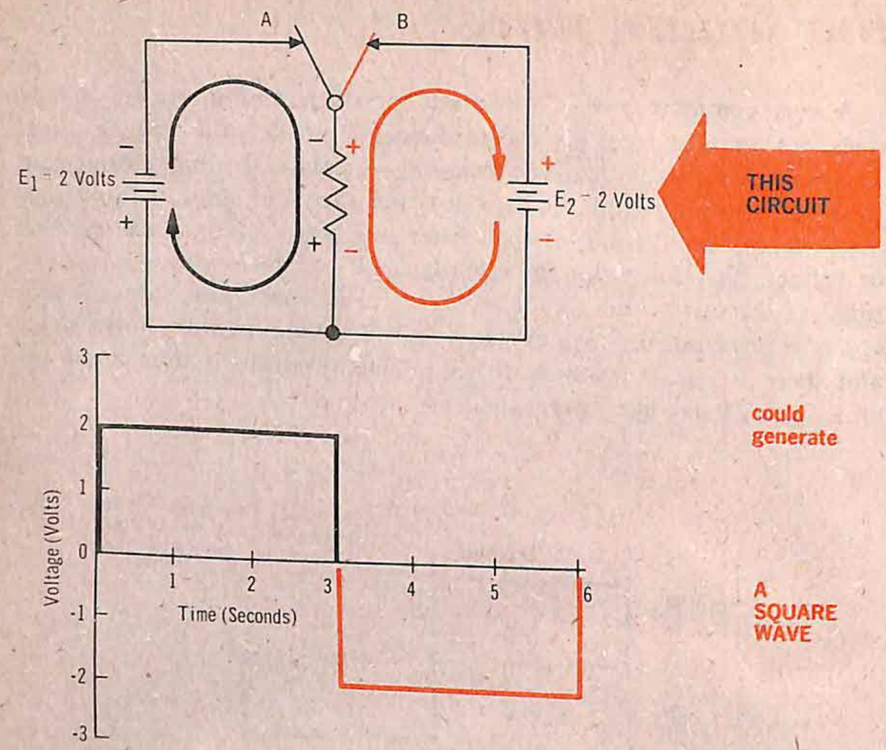
The vertical lines of a square wave correspond to the current or voltage instantly changing between its maximum values and zero

The horizontal lines correspond to steady values of maximum current or voltage

If a square wave was greatly expanded with respect to the time axis, the vertical lines would actually be sloping lines, because the current or voltage cannot change in value instantly. There would be a definite time required for the changes



Actually, the current or voltage does *not* change between its maximum values and zero instantly. However, these changes are so fast, that for all practical purposes they can be considered as happening instantly. You will find that this is very often true in the field of electricity. Many things happen so quickly that they can be considered, and will be called *instantaneous*, even though they are actually not.



THIS CIRCUIT

could generate

A SQUARE WAVE

generation of a square wave

If a switch in the circuit is alternately flipped between A and B, the waveform of the voltage across the resistor will be a square wave. For example, when the switch is first set in position A, the current flows from battery E_1 through the resistor, and instantly 2 volts are dropped across the resistor. This voltage stays at 2 volts as long as the switch is at A.

If after 3 seconds the switch is flipped to B, the voltage across the resistor caused by the current from E_1 drops to zero. Current from E_2 then flows through the resistor in the opposite direction, and causes 2 volts to be dropped across the resistor. This 2 volts is opposite in polarity to that previously caused by E_1.

If after 3 seconds, the switch is moved away from position B, the current from E_2 stops and the voltage across the resistor drops to zero. The voltage across the resistor has then completed one full square wave. If the switch was put back to position A and the process repeated, another square wave would be generated.

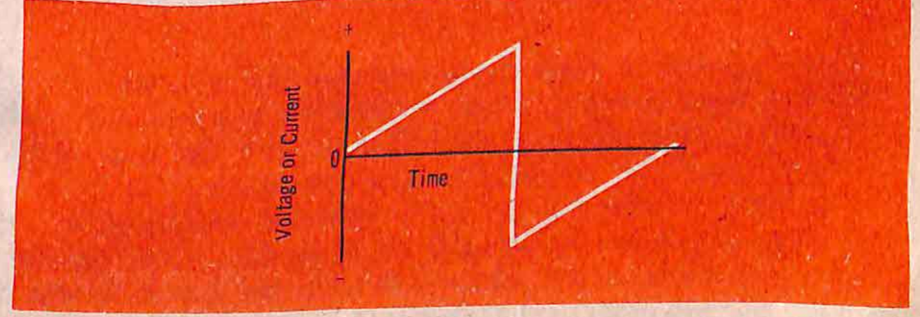
the sawtooth wave

You have probably noticed that waveforms get their names from their shapes. Thus, a square wave is square, or possibly rectangular, and a sine wave is sinusoidal. There is another very common waveform, which once you hear its name, you will probably have a good idea of its shape. This waveform is called the *sawtooth* wave, and looks very much like a tooth on a common wood saw.

To understand how a sawtooth wave is produced, you first have to know what a *linear* increase in current or voltage is. You already know that an instantaneous change in current or voltage is represented on a waveform by a *straight vertical line*. Curved lines on a waveform, such as a sine wave, show that the current or voltage is changing in a *nonlinear* way. This means that in each *equal increment*, or piece, of time, the current or voltage changes by a *different amount*. For example, in the first second current may rise from 0 to 5 amperes, or increase 5 amperes; in the next second it may go from 5 to 8 amperes, or increase 3 amperes; and in the next second it may rise to 10 amperes, or increase 2 amperes. In equal increments of 1 second, the current thus rose 5, 3, and 2 amperes. This is a *nonlinear* change in current.

To change linearly, the current or voltage must change by *equal amounts* in *equal time intervals*. This means that in the above example, the current would have to go from 0 to 5 amperes in the first second, from 5 to 10 amperes in the second second, and from 10 to 15 amperes in the third second. Its linear increase would then be 5 amperes per second. On a waveform, a linear change in current or voltage is represented by a *straight sloping* line.

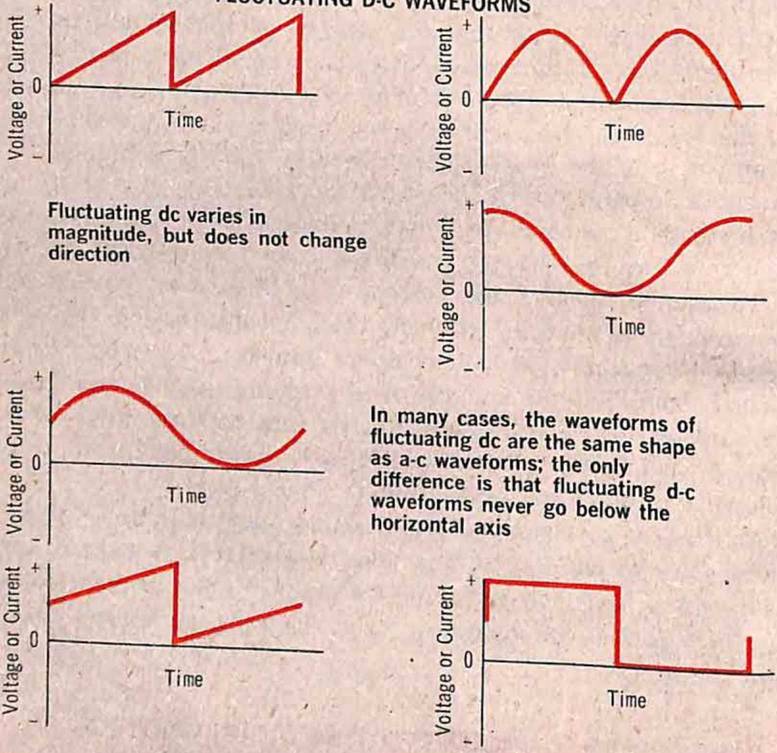
The sawtooth wave starts at zero, and linearly increases to its maximum value in one direction. It then instantly drops to zero, reversing its direction, and increases to its maximum value in this direction. The instant it reaches its maximum value, it begins to linearly decrease to zero again.



fluctuating dc

You know that every current has a *magnitude* and a *direction*. For direct current, both the magnitude and direction are constant and never change. For alternating current, on the other hand, both of them do change, with the direction reversing periodically, and the magnitude varying between zero and some maximum value in both directions. There is another type of current in which the *magnitude varies* but the *direction never changes*. This current is called *fluctuating dc*, since it can be considered a direct current that fluctuates, or changes, in value.

FLUCTUATING D-C WAVEFORMS

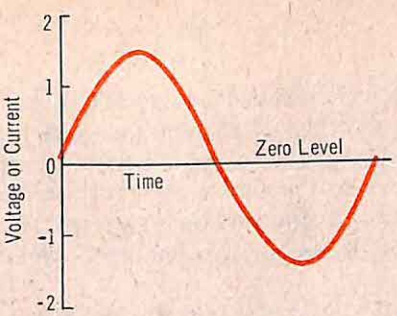


Fluctuating dc varies in magnitude, but does not change direction

In many cases, the waveforms of fluctuating dc are the same shape as a-c waveforms; the only difference is that fluctuating d-c waveforms never go below the horizontal axis

Since fluctuating dc never changes direction, the waveform of any fluctuating direct current or voltage is completely above the horizontal axis (zero). It never goes below the axis, or negative. The shape of the waveform, though, can be similar to any a-c waveform.

You will learn later that the characteristics of fluctuating dc are much more like those of ac than they are of dc. That is why this type of current is covered in this volume with ac, rather than in Volume 2 with dc.



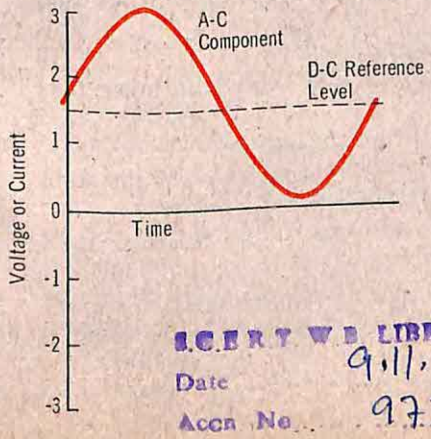
An a-c voltage or current changes in magnitude in one direction the same way that it changes in magnitude in the other direction. It, therefore, varies around a zero voltage or current level

the a-c component

Fluctuating dc is similar to regular dc in that it does not change direction. It is also similar to ac, since it varies in magnitude. Some types of fluctuating dc can be considered as *combinations* of ac and dc. In actual electric circuits, this is often the case. A d-c voltage or current is combined with an a-c voltage or current, and fluctuating dc is produced. When this is done, the dc varies in magnitude in an a-c way. The a-c variation is called the a-c component, and the dc is called the *d-c reference level*.

The waveform for such a voltage or current is identical to an a-c waveform, except that it is entirely *above* the horizontal axis. The d-c reference for this type of waveform is the horizontal line that half of the waveform is above and the other half is below. Thus, the a-c component varies *around* the d-c reference.

The a-c component can be removed from its d-c reference and be converted to a pure a-c voltage or current that varies around zero by devices called *transformers* and *capacitors*. These devices will be covered later.



When a d-c voltage or current varies in an a-c way, it does not change direction. However, it fluctuates around the d-c reference level in exactly the same way that ac fluctuates around the zero level

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summary

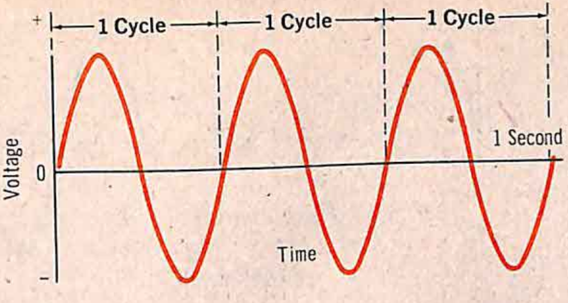
☐ Angular motion is motion in a circle. ☐ A circle is divided into 360 degrees. ☐ A waveform shows the magnitude and direction of current and voltage at every instant of time. ☐ The direction and magnitude of a d-c current or voltage never change. ☐ The voltage produced by the simple a-c generator has the sine wave as its characteristic waveform. ☐ The sine wave has symmetrical positive and negative portions above and below the zero reference level.

☐ If a waveform is not symmetrical about the horizontal axis, it is not pure ac. ☐ An a-c current or voltage is one which periodically changes direction, and which varies in magnitude in one direction exactly the same as it does in the other direction. ☐ The square wave increases instantly from zero to a maximum value. It stays at this maximum value for a period of time, decreases instantly to zero, and increases to a maximum value in this opposite direction. It stays at this negative maximum value for a period of time and then decreases instantly to zero.

☐ The sawtooth wave increases linearly from zero to a maximum value. It then instantly drops to zero, reversing its direction, and increases to a maximum value in this opposite direction. When it reaches this negative maximum value, it linearly decreases to zero again. ☐ Fluctuating dc changes in value, but never goes below the horizontal axis. ☐ A fluctuating d-c voltage can be considered to be made up of an a-c component varying above and below a d-c reference level. ☐ The a-c component can be removed from the d-c reference level by devices such as transformers and capacitors.

review questions

1. What is *angular motion*? How is it expressed?
2. With respect to the reference radius, in what direction does the rotating radius rotate?
3. What does a waveform show? Which axis is usually the time axis?
4. What is a *sine wave*? Why is it so called?
5. Is a d-c wave symmetrical above and below the horizontal axis?
6. What is a *square wave*? A *sawtooth wave*?
7. Can a square wave be generated by a battery? What additional components are necessary besides the battery?
8. What is *fluctuating dc*? Does it ever go below the horizontal axis?
9. Draw the waveform of a fluctuating d-c voltage.
10. What is meant by the *a-c component*? *D-c reference level*?



The frequency of a voltage or current is the number of cycles generated each second. The frequency of this voltage is, therefore, 3 cps

frequency

In an a-c waveform, the variation of voltage or current from zero to a maximum and back to zero, say, in the positive direction, and from zero to a maximum and back to zero, say, in the negative direction, is one complete *cycle*.

The number of cycles generated in 1 second is called the *frequency* of the voltage or current, and is expressed in *cycles per second, cps.* The greater the number of cycles produced in one second, the higher is the frequency. This means that the *faster* the generator armature turns, the *more cycles* it generates in each second, and so the *higher* is the *frequency* of the output voltage. If the simple generator turned at a speed of 10 revolutions per second, the frequency would be 10 cps; at 100 revolutions per second, the frequency would be 100 cps.

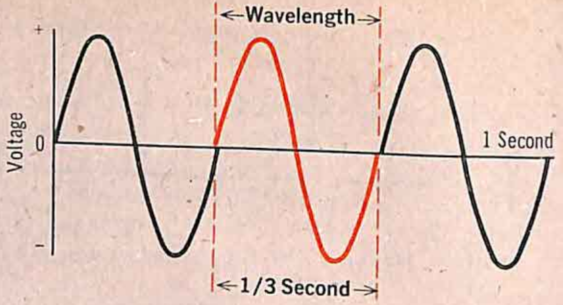
Most of the electric power generated in the United States has a frequency of 60 cps. On most electrical appliances there is a statement that the appliance is to be used only on 60 cps ac. These appliances are designed for this standard power frequency, and if they are connected to a power source that has a different frequency, they will either be damaged or not work properly.

Electric power frequencies used in other countries vary anywhere from 25 to 125 cps. For example, many of the countries in Europe and South America have a standard electric power frequency of 50 cps. In some *special* cases, for example in an aircraft electrical system, the electric power frequency may be from 400 to 1000 cps.

CONVERSION OF UNITS

1 kilocycle (kc) = 1000 cps
cps/1000 = kc
cps/1,000,000 = mc
kc/1000 = mc

1 megacycle (mc) = 1,000,000 cps
kc × 1000 = cps
mc × 1,000,000 = cps
mc × 1000 = kc



Since the frequency of the voltage is 3 cps, the wavelength is

Wavelength (meters)
= 300,000,000 ÷ frequency
= 300,000,000 ÷ 3
= 100,000,000 meters

As the frequency decreases, the wavelength becomes longer

wavelength

You remember from Volume 1 that, although the individual electrons that make up electric current move through a wire quite slowly, the electric field, or impulse, that causes the current flow, moves down a wire at about 186,000 miles per second. Since the current travels at a definite speed, it can only travel a certain *distance* during any period of *time*. And since frequency is actually a measure of the number of *cycles* for a given period of *time*, you can calculate how far current can travel during 1 cycle of a-c voltage. This distance is called the *wavelength*. It is the *distance* that current can move in the time it takes to complete 1 full cycle of a-c voltage.

With a 60-cps voltage, for example, 1 cycle takes 1/60th of a second. And, since current travels 186,000 miles in one second, it can only travel 3100 miles during 1/60th of a second, or 1 cycle of a 60-cps a-c voltage. The wavelength of a 60-cps voltage, therefore, is 3100 miles. Since the wavelength of a-c voltage depends on its frequency and the speed at which the electric impulse moves along a wire, it can be calculated by the equation:

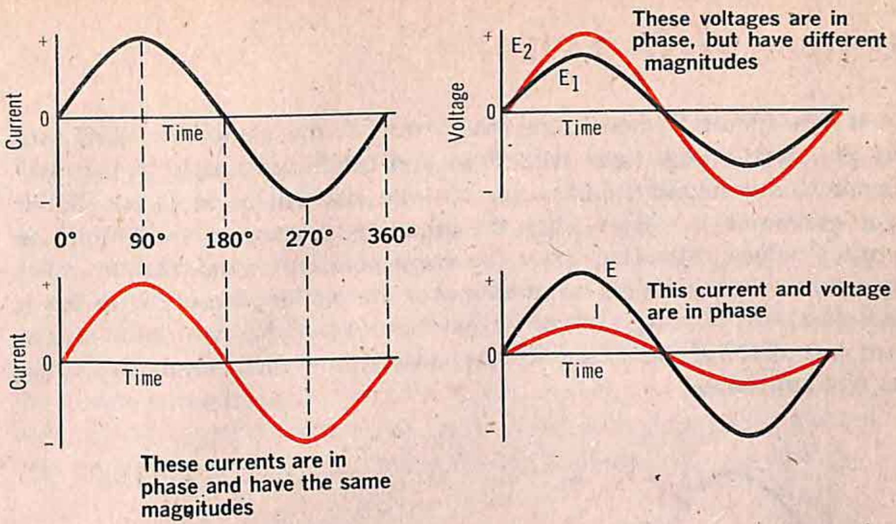
$$\text{Wavelength} = \text{velocity of current}/\text{frequency}$$

The velocity of current, as far as basic electricity is concerned, is the speed of light: 186,000 miles per second. However, for many years, it has been standard practice to use the metric system for the speed of light. In the metric system, the basic unit for distance is the *meter*; 1 meter equals 39.37 inches, so that the speed of light is 300,000,000 meters per second. The equation for wavelength then becomes:

$$\text{Wavelength (meters)} = 300{,}000{,}000/\text{frequency}$$

The wavelength for 1 cycle of a 60-cps voltage is now said to be 5,000,000 meters.

You can see that *wavelength* is just another way of expressing *frequency*. The use of wavelength is not too important in electrical power but it is often used in the field of communications.



Current and voltages are in phase when they both reach their maximum values and their minimum values at the same time

phase

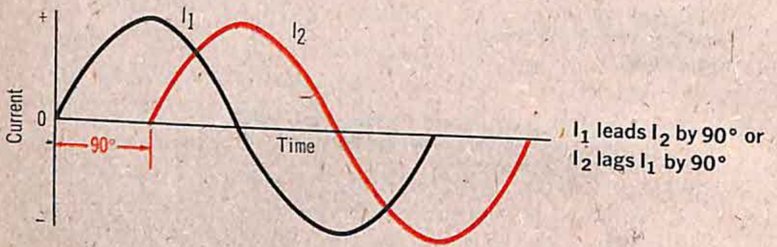
The output of a simple a-c generator varies as a sine wave. Therefore, if two such generators are started, they each will generate one full sine wave output after one full revolution. If the generators are started at the *same time* and turn at exactly the *same speed*, the two waveforms will *begin* simultaneously and *end* simultaneously. They will also reach their maximum values and pass through zero at the same time. The two waveforms are thus "in step" with each other, and the voltages they represent are said to be *in phase*. From this you can see that the term *phase* is used to indicate the *time* relationship between alternating voltages and currents.

When two currents or voltages are in phase, it does not mean that their *magnitudes* are the same. The peak magnitudes are reached at the same time, but they can have different values.

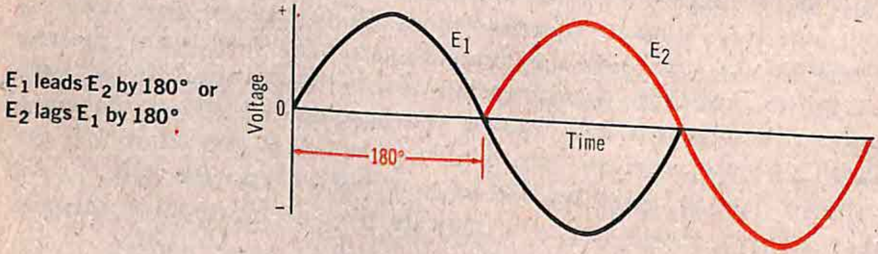
Although phase is usually used to compare the time relationship of two waveforms, it can also be used to indicate a point in time for one waveform. As shown on page 3-15, a full cycle can be represented by degrees. These degrees are often called *phase angles*. The phase of the positive peak is 90 degrees, and the negative peak is 270 degrees. The sine wave is zero at the phase angles of 0, 180, and 360 degrees. In this way, any point on a sine wave can be referred to as some phase angle.

phase difference

If two identical generators are started at the same time and turn at the same speed, their maximum and minimum output values will occur simultaneously, and so the two outputs will be *in phase*. But if one generator is started after the other, its maximum and minimum output values will occur *after* the corresponding values for the other generator. The two outputs in this case are *out of phase*. Or, to put it another way, a *phase difference* exists between the two outputs. The amount of the phase difference depends on how far behind one output is from the other.



When maximum and minimum points of one voltage or current occur before the corresponding points of another voltage or current, the two are out of phase. When such a phase difference exists, one of the voltages or currents leads, and the other lags



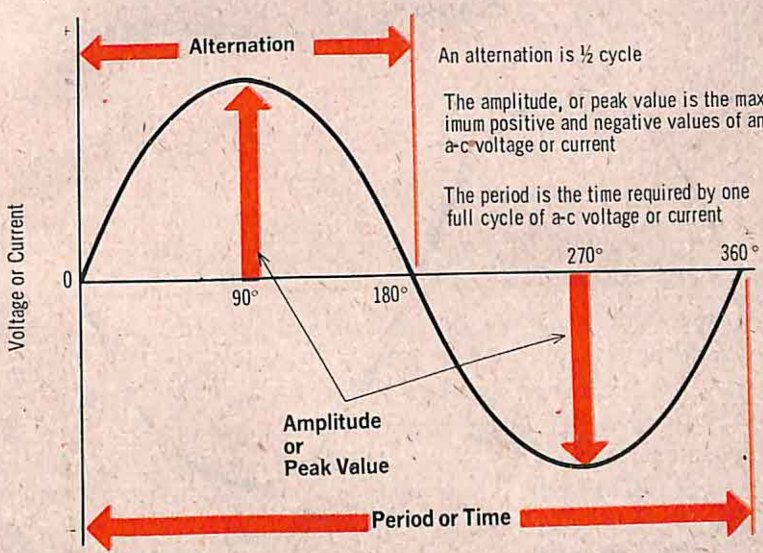
Phase difference can be expressed in fractions of a cycle. Then, if one output begins when the other has just completed one-half of a cycle, the phase difference is one-half cycle. Usually though, for more accuracy, phase difference is given in *degrees*. And since one full sine wave corresponds to 360 degrees, a phase difference of one-half cycle is a 180-degree phase difference; a one-quarter cycle difference is a 90-degree phase difference, etc.

The terms *lead* and *lag* are used to describe the relative positions in time of two voltages or currents that are out of phase. The one that is *ahead* in time is said to *lead*, while the one *behind lags*.

other a-c terms

You are already familiar with most of the terms normally used to describe a-c voltages and currents and their waveforms. However, in addition to *cycle, frequency, wavelength,* and *phase,* there are other a-c terms that are used very often, which you should know. For example, ½ of a full cycle is often referred to as an *alternation.*

Another term is *amplitude.* The amplitude of an a-c current or voltage is the *maximum value* that the current or voltage reaches. It is the same in both the positive and negative directions. On a waveform, the amplitude is the distance from the horizontal axis to either the highest point of the wave above the axis, or to the lowest point below the axis. The amplitude is often also called the peak value.



An alternation is ½ cycle

The amplitude, or peak value is the maximum positive and negative values of an a-c voltage or current

The period is the time required by one full cycle of a-c voltage or current

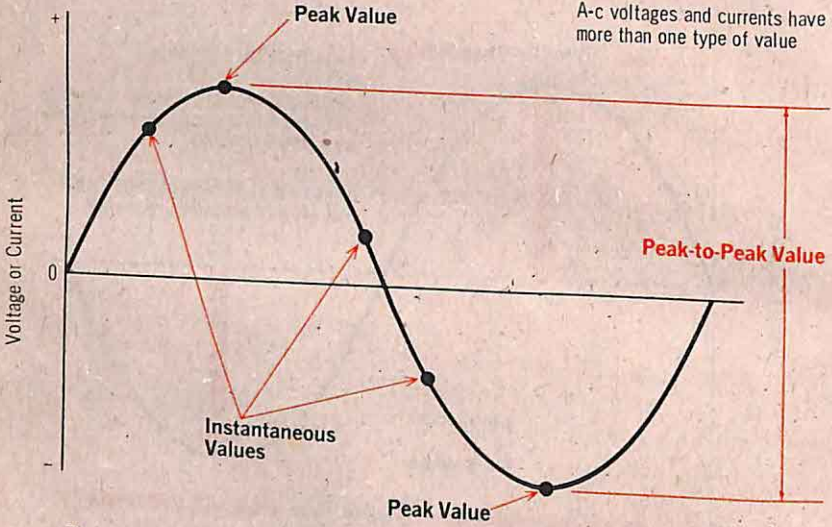
Another term you should know is *period.* The period of an alternating quantity, such as a-c voltage or current, is the *time* it takes to complete *one full cycle* of the quantity. If you know the frequency, the period can easily be calculated. For example, for a 60-cps voltage, 60 cycles are generated in one second. It therefore takes 1/60 of a second to generate one cycle. Thus, you obtain the period by dividing the frequency into 1.

$$\text{Period} = \frac{1}{\text{frequency}}$$

The period is in seconds, and the frequency is in cycles per second, cps.

values of a-c voltage and current

To specify the value of a d-c voltage or current is no problem, since d-c values do not change. The values of a-c voltages and currents, though, are constantly changing, and so there is a problem when it comes to specifying them. Before you can give the value of an a-c voltage or current, you usually have to determine what type of value is needed. And this in turn depends on how you want to use the value. The most obvious value to you is probably the *peak value*, which you know is the *amplitude* or maximum value of the voltage or current. Another value sometimes used is the peak-to-peak value, which is twice the peak value. On a waveform, the peak-to-peak value is the distance from the maximum positive value to the maximum negative value.



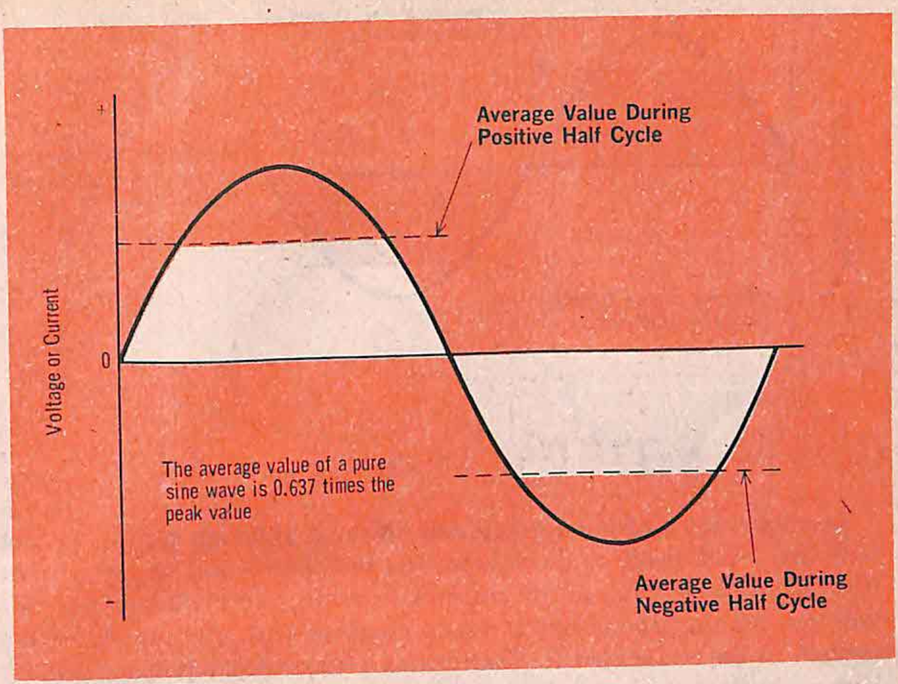
A-c voltages and currents have more than one type of value

Three shown here are the peak values, the peak-to-peak value, and the instantaneous values

Two others not shown are the average value and the effective value

Occasionally, you might be interested in the *instantaneous value* of the voltage or current. This is the value at one particular instant of time; and depending on the instant you select, it can range anywhere from zero to the peak value.

In most cases, none of these values (peak, peak-to-peak, or instantaneous) are satisfactory for giving the actual values of a-c voltages and currents. Instead, two other values, called the *average* and the *effective* values, are generally used.


Average Value During Positive Half Cycle
Voltage or Current
+
0
-
The average value of a pure sine wave is 0.637 times the peak value
Average Value During Negative Half Cycle

average values

The average value of an a-c voltage or current is the *average* of all the instantaneous values during *one half cycle*, or alternation. Since during a half cycle, the voltage or current increases from zero to the peak value and then decreases back to zero, the average value must be somewhere between zero and the peak value. For a pure sine wave, which is the most common waveform in a-c circuits, the average value is 0.637 times the peak value. For voltage, this is expressed by the equation:

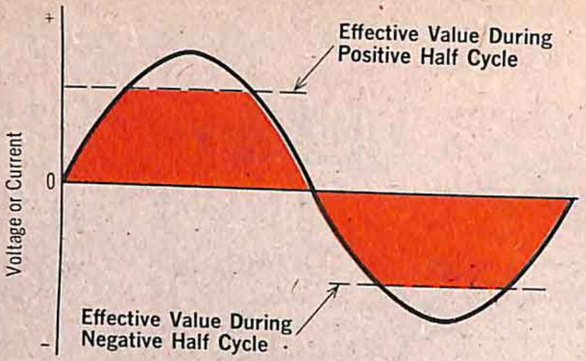
$$E_{AV} = 0.637\ E_{PK}$$

As an example, if the peak voltage in a circuit is 100 volts, the average voltage will be:

$$E_{AV} = 0.637\ E_{PK} = 0.637 \times 100 = 63.7 \text{ volts}$$

The equation for average current in terms of peak current is identical to that for voltage.

You should be careful never to confuse average value, which is the average of *one-half cycle*, with the average over a *complete cycle*. Since both half cycles are identical, except that one is positive and the other negative, the average over a *complete cycle* would be *zero*.


Effective Value During Positive Half Cycle
Voltage or Current
+
0
-
Effective Value During Negative Half Cycle

The effective (rms) value of a pure sine wave is 0.707 times the peak value

effective values

Average values of a-c voltage and current, although useful, do not have any relationship to d-c values. You may know that an a-c current with an average value of 10 amperes is flowing in a circuit, but this tells you nothing about how it would compare with 10 amperes of d-c current in the same circuit. Since many electrical equipments contain both a-c and d-c circuits, it is very useful to be able to express a-c currents and voltages in values related to dc. This is possible with the use of *effective values*.

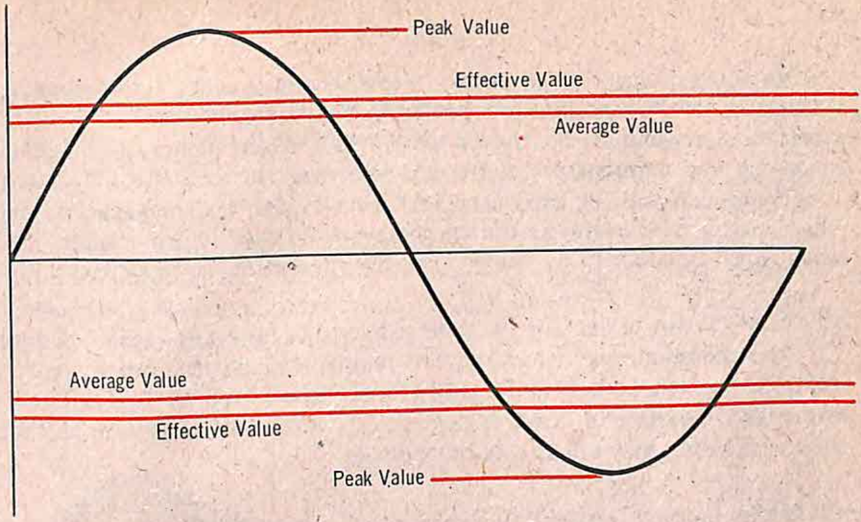
The effective value of an a-c voltage or current is the value that will cause the same amount of *heat* to be produced in a circuit containing only resistance that would be caused by a d-c voltage or current of the same value. Thus, an alternating current with an effective value of 1 ampere generates the same heat in a 10-ohm resistor as does a direct current of 1 ampere. The effective value is also called the *root-mean-square*, or *rms*, value because of the way it is derived. It is equal to the square root of the average value of the squares of all the instantaneous values of current or voltage during one-half cycle.

In a pure sine wave, the effective value is 0.707 times the peak value. The equations for the effective values of current and voltage are, therefore,

$$I_{EFF} = 0.707\ I_{PK} \qquad E_{EFF} = 0.707\ E_{PK}$$

Therefore, for a peak voltage of 100 volts, an a-c voltage would have an rms value of 70.7 volts. This means that a resistor that is put across a 100-volt a-c source will produce the same heat as if it were placed across a 70.7-volt d-c source.

The effective value is the one that is usually used to rate a-c voltage and currents. The home line voltage of 110 volts is the *rms* value. And so is the 220-volt industrial power voltage.



converting values

In working with a-c circuits you will often have to *convert* given or measured values of a-c voltage or current to other values. For example, you may have to convert an average value to a peak value, or maybe an effective value to an average value. For all conversions between peak, average, and effective values, there are six basic equations that apply. By using the proper equation, you can easily convert from any one of these values to any other. The six equations are given below for converting voltage and current values.

CONVERTING A-C VOLTAGES AND CURRENTS

To Convert From	To	Use the Equations	
Peak	Average	$E_{AV} = 0.637\ E_{PK}$	$I_{AV} = 0.637\ I_{PK}$
Peak	Effective	$E_{EFF} = 0.707\ E_{PK}$	$I_{EFF} = 0.707\ I_{PK}$
Average	Peak	$E_{PK} = 1.57\ E_{AV}$	$I_{PK} = 1.57\ I_{AV}$
Average	Effective	$E_{EFF} = 1.11\ E_{AV}$	$I_{EFF} = 1.11\ I_{AV}$
Effective	Peak	$E_{PK} = 1.414\ E_{EFF}$	$I_{PK} = 1.414\ E_{EFF}$
Effective	Average	$E_{AV} = 0.9\ E_{EFF}$	$I_{AV} = 0.9\ I_{EFF}$

In some cases, you may have to convert from or to peak-to-peak values. To do this it is best to use the equations for the peak value, and remember that the peak-to-peak value is twice the peak value, and conversely that the peak value is one half the peak-to-peak value.

summary

☐ The number of cycles generated in one second is called the frequency of a voltage or current, and is expressed in cycles per second, cps. ☐ Most of the electric power generated in the United States has a frequency of 60 cps. Other countries use different power frequencies, ranging from 25 to 125 cps. ☐ Frequency can also be expressed in kilocycles, kc; and megacycles, mc. ☐ The distance a wave travels during one cycle is called its wavelength. ☐ The wavelength is equal to the wave's velocity divided by its frequency.

☐ Phase is used to indicate the time relationship for a-c voltages and current. ☐ Phase difference expresses the time relationship between two voltages, currents, or combinations of both, with respect to each other. This difference is expressed in parts of a cycle, or degrees. ☐ When two waveforms are in step with each other, they are said to be in phase.

☐ An alternation is one-half of a complete cycle. ☐ The time it takes to complete one full cycle is the period of the waveform. Period equals 1/frequency. ☐ The average value for one alternation (1/2 cycle) of a sine wave is equal to 0.637 times the peak value. The average for a complete cycle is zero. ☐ For a pure sine wave, the effective, or rms, value is equal to 0.707 times the peak value.

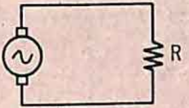
review questions

1. What is the frequency most commonly used for electric power in the United States?
2. Frequency is measured in what units?
3. What ~~is~~ meant by *phase*? *Phase difference*?
4. Define *amplitude* and *alternation*.
5. What is the effective value of a voltage whose maximum amplitude is 200 volts?
6. What is the rms value of a voltage whose peak-to-peak voltage is 200 volts?
7. What is the average value of the output voltage of a 6-volt battery? The rms value?
8. The average value of a sine-wave current is 5 amperes. What is its peak, effective, and peak-to-peak values?
9. One alternation of a sine wave takes 4/1000 of a second. What is the frequency of the wave?
10. What is the maximum value of a sine wave whose effective value is 50 volts? Whose peak-to-peak value is 50 volts? Whose average value for one alternation is 50 volts?

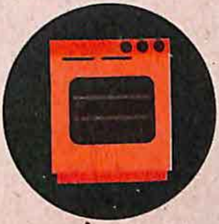
resistive a-c circuits

In a d-c circuit, the only property that opposes or reduces current flow is resistance. Resistance also affects the current flow in a-c circuits, although it is not always the only property that does. You will learn later that a-c circuits have other properties, which, like resistance, affect the current and voltage throughout a circuit. The *simplest* type of a-c circuit, though, contains *only resistance*. And like a d-c circuit, this resistance includes the individual resistances of the loads, the power source, and the connecting wires.

An a-c resistive circuit is one that contains only resistance



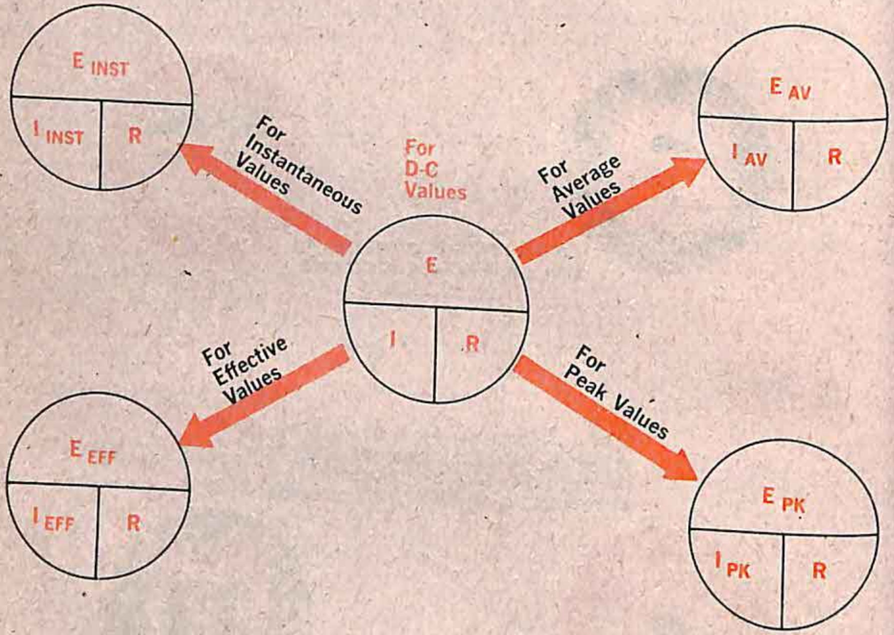
Electric appliances used to produce heat, such as toasters, irons, frying pans, and ranges, are examples of a-c resistive circuits when they are connected to the standard home power source



In actual practice, no a-c circuit can contain only resistance. The other properties that affect the voltage and current are always present in some amount. However, when their effects are very small compared with the effects of the resistance, they can be considered as being not present. The circuit is then a completely *resistive* circuit.

current and voltage

When an a-c voltage is applied across a resistance, an a-c current flows through the resistance. The magnitude of the *current* at any instant is *directly proportional* to the magnitude of the *voltage* at that instant, and is *inversely proportional* to the value of the *resistance*. This is the same relationship that exists between the current, voltage, and resistance in a d-c circuit, and so *Ohm's Law* also applies to the *instantaneous* values of current and voltage in an a-c circuit.

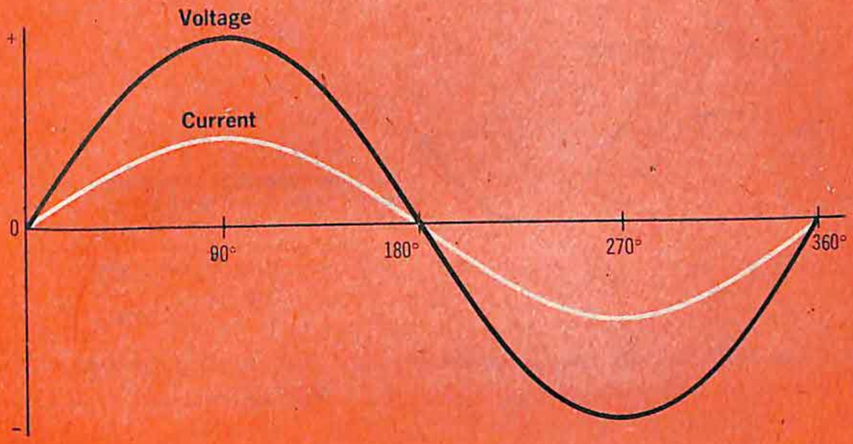


In a-c circuits that contain only resistance, the relationship between the current, voltage, and resistance is that of Ohm's Law

Since the average, effective, and peak values of a-c current and voltage are derived from the instantaneous values, Ohm's Law also applies to them. This means that to find resistances, currents, and voltages in a-c resistive circuits, you use the same rules and methods that you learned for d-c circuits in Volume 2.

phase relationships

Since the instantaneous values of current and voltage in an a-c circuit that contains only resistance follow Ohm's Law, this means that at any instant when the voltage is zero, the current is also zero. And when the voltage is maximum, the current must also be maximum, since the resistance is constant. When the voltage reverses and becomes negative, the current also reverses, inasmuch as it always flows from negative to positive. Thus, at every *instant* of time the current is exactly *in step* with the applied voltage.

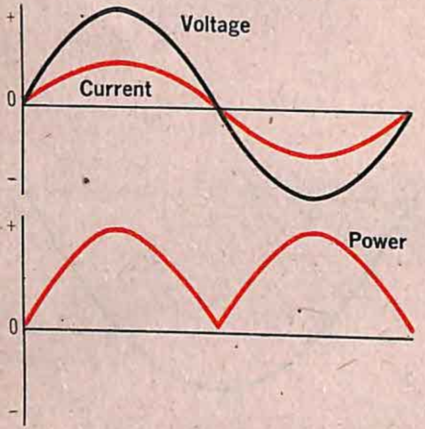


In a-c resistive circuits, the voltage and current are in phase everywhere in the circuit. Both of them are zero at the same instant and reach their maximum values at the same instant. This in-phase relationship is maintained throughout the entire cycle

In an a-c resistive circuit, therefore, the current and voltage are *in phase*. This is true not only of the total circuit current and the source voltage, but is so for the voltage and current in *every part* of the circuit.

power

The power consumed in any circuit depends on the voltage and current in the circuit. And since in a purely resistive circuit, a-c voltages and currents follow Ohm's Law, it would seem that the power in such a circuit would be calculated in the same way as the power in a d-c circuit. Essentially, this is true. The power in an a-c resistive circuit does follow the standard d-c equation $P = EI$. However, a-c voltages have different types of values, and so, therefore, does a-c power.



The value of each point on the power waveform is equal to the product of the voltage and current at that instant. The second half cycle of the power waveform is positive since it is produced by the product of two negative quantities

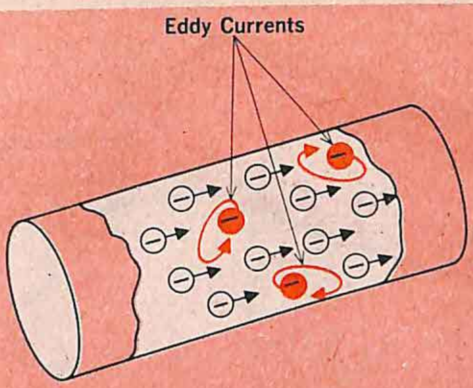
At any particular instant, the power in an a-c resistive circuit is equal to the product of the voltage and current at that instant. This is the *instantaneous power* and is found by the equation $P_{INST} = E_{INST}I_{INST}$. The instantaneous power can range anywhere from zero, if the current and voltage at that instant are zero, to the peak power, if the current and voltage are at their peak values at that instant.

Usually, you will not be interested in instantaneous power, but in the power used during a full cycle. This is often referred to either as *power* or *average power*. To find this, you would use the *effective* or *rms* values of voltage and current, since these values are the ones that give the same power loss effect as the d-c equivalent, as you learned earlier. The formula, then, for finding this power dissipated in a circuit is

$$P = E_{EFF}I_{EFF}$$

Another formula that can be used if you know the peak value is

$$P = \frac{E_{PK}I_{PK}}{2}$$

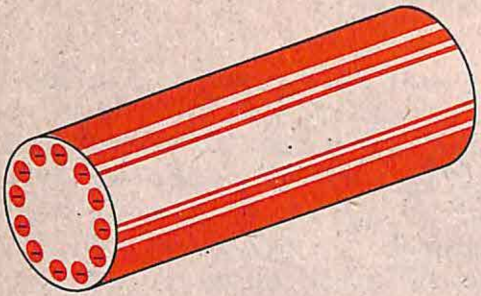


Eddy currents do not add to the main current through a conductor, but nevertheless cause power to be consumed. They, therefore, represent an increase in conductor resistance

eddy currents and skin effect

In d-c circuits, resistance is a physical property of the conductors that opposes current flow. The resistance is directly proportional to conductor length and inversely proportional to conductor cross-sectional area. This d-c, or *ohmic*, resistance opposes a-c current the same as it does d-c current. However, when a-c current flows in a conductor, the resistance offered to the current by the conductor is somewhat *greater* than the resistance that would be offered to d-c current by the same conductor. There are two reasons for the increase in resistance, and both are due to the fact that when an a-c current flows in a conductor, it causes *voltages* to be set up inside of the conductor. How this is done will be explained later in this volume. The voltages set up in the conductor cause small independent currents, called *eddy currents*, to exist. These eddy currents flowing through the resistance of the conductor consume power, and therefore represent a *power loss*, or an increase in resistance, in the circuit.

Besides producing eddy currents, the voltages set up in a conductor by a-c current repel the flowing electrons towards the *surface* of the conductor. See illustration on page 3-38. More current, therefore, flows near the conductor surface than at the center of the conductor. This has the effect of *decreasing* the *cross-sectional area* of the conductor, and as you have learned, a decrease in cross-sectional area causes an increase in resistance. The concentration of current flow near the surface of a conductor is called *skin effect*.

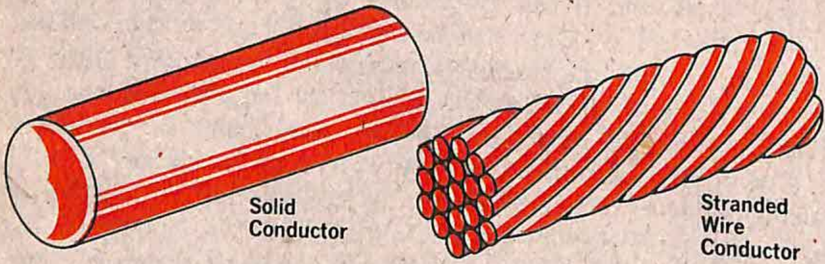


Skin effect results in a higher concentration of current near the conductor surface than at the conductor. Effectively, this reduces the cross-sectional area of the conductor

A-C Resistance = D-C Resistance + Eddy Current loss + Skin Effect Loss

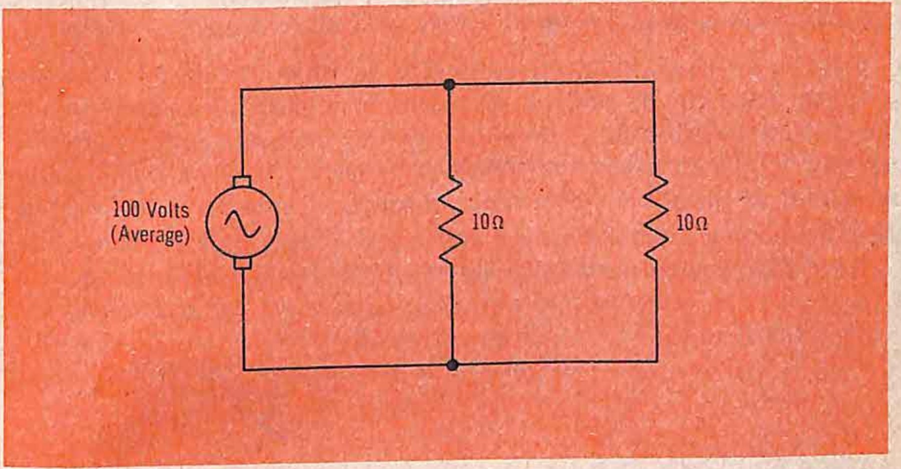
eddy currents and skin effect (cont.)

The losses in a-c conductors due to eddy currents and skin effect are *directly proportional* to the *frequency* of the current flowing in the conductor. The higher the frequency, the greater are the eddy current and skin effect losses. These losses only become significant when the frequency is very high. For this reason, they will be considered as zero, and therefore neglected in the remainder of the volume. Power cables are usually made of *stranded wires* to reduce the skin effect loss. This works because the surface areas of all the individual wire strands added together is greater than the surface area of a solid conductor.



Skin effect loss is reduced in power cables by the use of stranded wire. The total surface area of the wires is greater than that of a single conductor

solved problems



Problem 1. What is the effective value of the total current in the circuit?

The effective value of the current is asked for, but the source voltage given is the average value. The average value could be converted to its equivalent effective value, and the effective current then calculated directly. Or, the current could be solved for the average current and the conversion to the effective value could then be made. Since only one conversion is required, it will be made first, although either method would be equally satisfactory in this problem.

The equation for converting average voltage to effective voltage can be taken from the table on page 3-31.

$$E_{EFF} = 1.11\ E_{AV} = 1.11 \times 100 \text{ volts} = \text{approx. } 110 \text{ volts}$$

The total resistance of the two 10-ohm resistors in parallel is 5 ohms, and so you know the effective value of the applied voltage and the circuit resistance. Since it is a purely resistive circuit, Ohm's Law can be used to find the effective current.

$$I_{EFF} = E_{EFF}/R = 110 \text{ volts}/5 \text{ ohms} = 22 \text{ amperes}$$

Problem 2. What is the peak value of the circuit current?

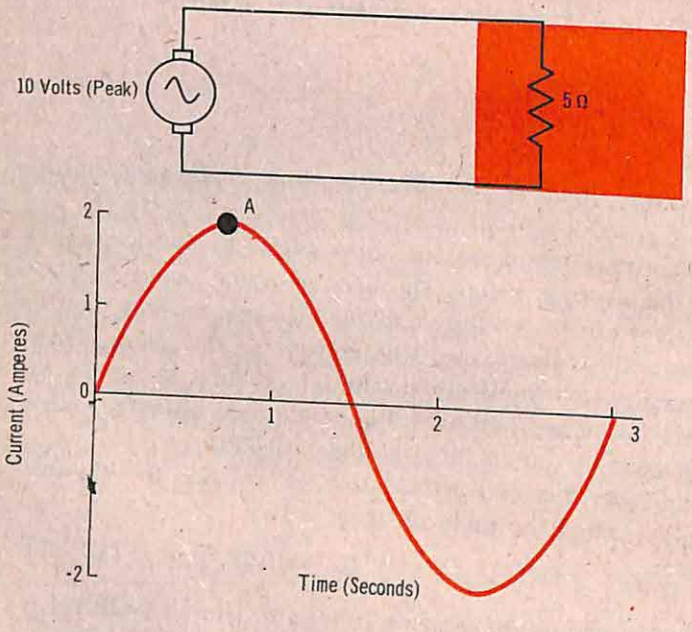
The effective current is 22 amperes. To convert this to its equivalent peak current, you use the appropriate equation from the table on page 3-31.

$$I_{PK} = 1.414\ I_{EFF} = 1.414 \times 22 \text{ amperes} = 31.11 \text{ amperes}$$

solved problems (cont.)

Problem 3. *The current in this circuit has a waveform as shown. What is the voltage across the resistance at instant A on the waveform?*

Point A on the waveform is the instant at which the current reaches its peak value in the positive direction. In a purely resistive circuit, the current and voltage are in phase; and so when the current reaches its peak in one direction, the voltage also reaches its peak in the same direction. At instant A, therefore, the source voltage is at its peak of 10 volts. The voltage across the resistance is also 10 volts, since the entire source voltage is dropped across the load in a series circuit.



Problem 4. *What is the power consumed in the circuit?*

The values of current and voltage could be converted to their equivalent effective values, and the power then calculated from the equation $P = E_{EFF}I_{EFF}$. However, since both values are peak, it is easier to use the equation that expresses power in terms of peak voltage and current. The equation is

$$P = \frac{E_{PK}I_{PK}}{2} = \frac{10 \text{ volts} \times 2 \text{ amperes}}{2} = 10 \text{ watts}$$

summary

☐ Ohm's Law applies to instantaneous values of current and voltage in an a-c circuit, just as in a d-c circuit. ☐ In an a-c resistive circuit, the current and voltage are in phase. ☐ The average power dissipated in a resistor in an a-c circuit is $P = E_{EFF}I_{EFF}$ and $P = E_{PK}I_{PK}/2$.

☐ Instantaneous power is found by the equation: $P_{INST} = E_{INST}I_{INST}$. It can range from zero to a maximum, which is reached when the current and voltage are both at their peak values at the same time, as is the case in a pure resistive circuit.

☐ The losses in a-c conductors due to eddy current and skin effect are directly proportional to the frequency of the current. Because these losses only become significant at high frequencies, they are neglected and considered to be zero in this volume. ☐ Power cables are usually constructed of stranded wires to reduce skin effect loss.

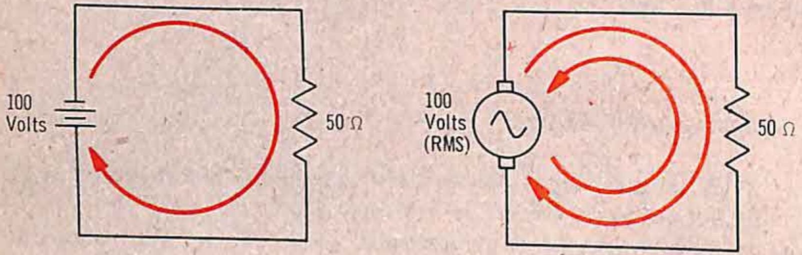
review questions

1. What are *eddy currents*? How are they related to frequency?
2. What is *skin effect*? Is it present in d-c circuits?
3. How is skin effect overcome in power cables? Why does this work?
4. What is the average power dissipated in an a-c circuit where the maximum voltage is 20 volts, and the maximum current is 40 amperes?
5. What is the average power dissipated in an a-c circuit where the effective voltage is 70 volts and the effective current is 30 amperes?
6. The instantaneous current through a resistor is 14 amperes, and the instantaneous voltage across the resistor is 28 volts. What is the instantaneous power developed?
7. The peak value of the voltage in an a-c circuit is 100 volts, and the effective current is 7 amperes. What is the average power dissipated?
8. The peak power developed across a resistor is 1500 watts, when the effective voltage across the resistor is 500 volts. What is the average current over one alternation?
9. The average value of one alternation of a sine-wave voltage is 75 volts, and the peak value of the current is 3 amperes. What is the average power developed?
10. The average power developed across a resistor is 2000 kilowatts, and the peak-to-peak voltage is 200 kilovolts. What is the value of the effective current through the resistor?

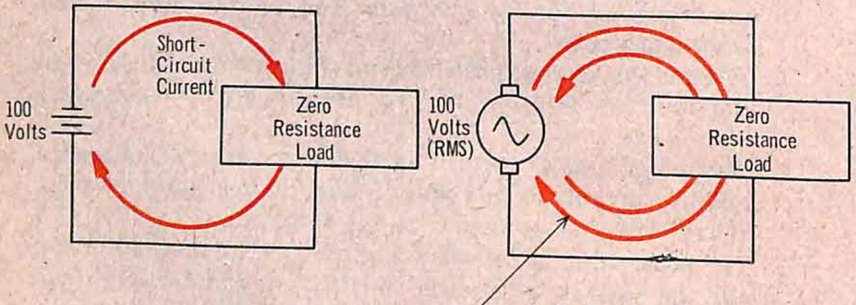
nonresistive a-c circuits

In a d-c circuit, resistance is the *only* thing that opposes current flow. Therefore, a d-c circuit *without* resistance, or with a very low resistance, is a *short circuit*. Damagingly high currents will flow in such a circuit, and no useful function can be accomplished. In a-c circuits, on the other hand, resistance is *not* the only thing that opposes current. Two other circuit properties, called *inductance* and *capacitance*, oppose the flow of a-c current. Therefore, if either of these properties are present, a-c current is *limited*, even though the circuit resistance may be zero.

IDENTICAL CURRENTS WILL FLOW

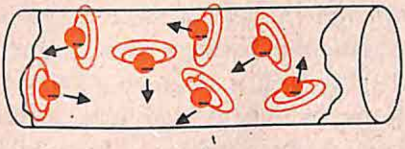


IDENTICAL CURRENTS WILL NOT NECESSARILY FLOW

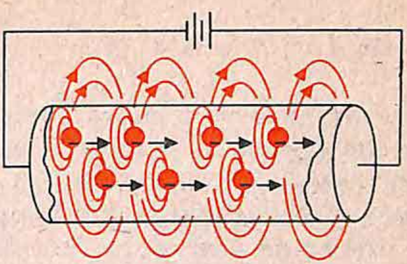


Current is limited by any inductance or capacitance present in the circuit

The nature and characteristics of inductance and capacitance are described in the remainder of this volume. Inductance is covered first, followed by capacitance. Before examining inductance, though, some of the basic principles of electromagnetism and its effects will be reviewed, since inductance is basically an electromagnetic phenomenon.



With no voltage applied and therefore no current, the magnetic fields of the free electrons cancel each other. There is no field outside the conductor



With a voltage applied, the free electrons move in the same direction, and their magnetic fields combine. The overall field extends outside the conductor

the magnetic field around a conductor

An electric current is made up of many free *electrons*, moving in the *same direction* in a wire. Each moving electron sets up its own magnetic field, and since the electrons are moving in the same direction, the fields of the individual electrons *combine* to produce one overall magnetic field.

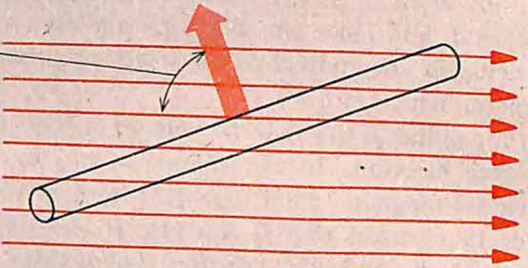
In a conductor that has no voltage applied to it, the current is zero. The free electrons in the conductor are moving and creating their individual magnetic fields, but their motion is *random*. At each instant, for every electron that is moving in one direction, there is another moving in the opposite direction. This causes the individual magnetic fields to oppose, or *cancel*, each other. As a result, there is no magnetic field outside of the conductor.

If a voltage is applied to the conductor, many of the free electrons begin moving in the same direction. Their individual magnetic fields then combine, and an overall field is produced. This magnetic field extends outside of the conductor, with each line of force making a circle, or loop, around the conductor. If the voltage applied to the conductor is increased, the current also increases. More electrons will then contribute to the overall magnetic field, and so its strength will be greater. The strength of a magnetic field is usually indicated by the number of individual lines of force, and their distance apart. Strong fields have many lines, and they are closely spaced.

The direction of the magnetic field around a current-carrying conductor is given by the *left-hand rule*, which you learned in Vol. 1: If you wrap your left hand around a conductor with your thumb pointing in the direction of the current flow, the magnetic field surrounding the conductor is in the direction of your curled fingers.

induced emf

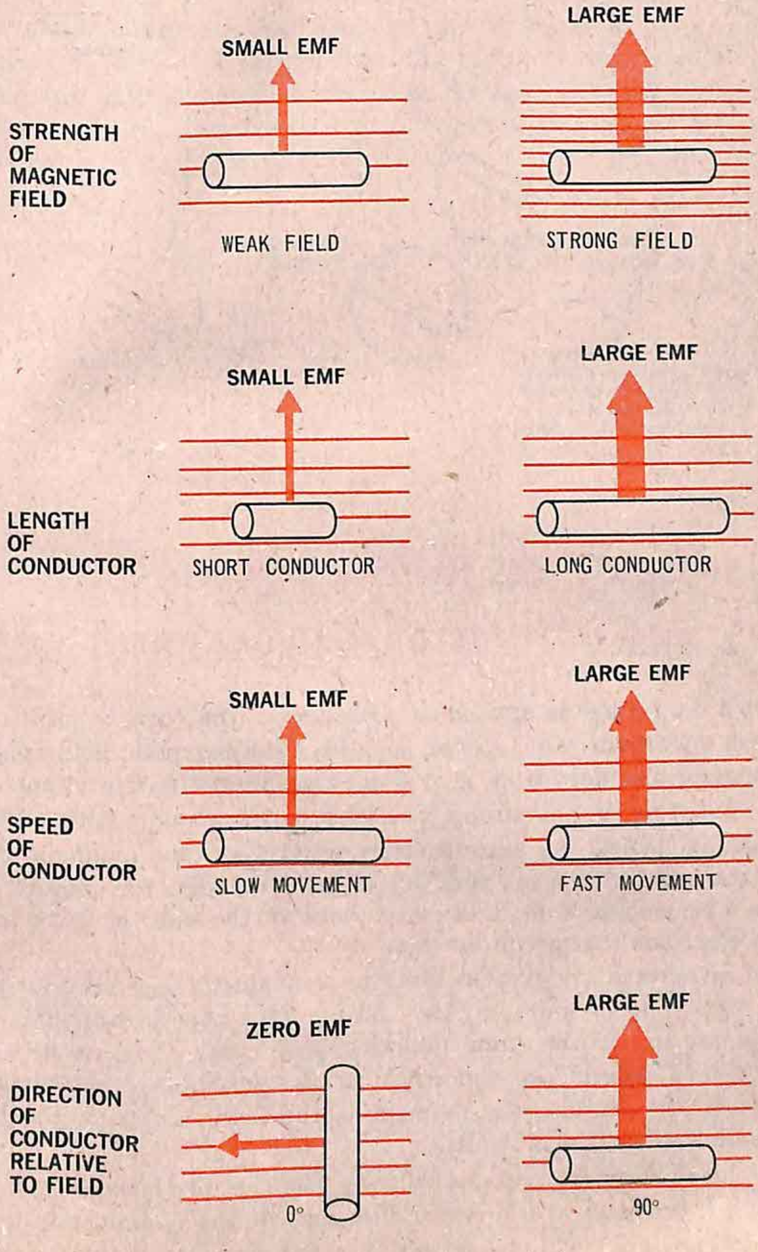
When an electron *moves* through a *magnetic field*, a force is exerted on the electron as a result of the interaction between the magnetic field of the electron and the field through which it is moving. When a piece of conductor is moved through a magnetic field, therefore, a force is exerted on *each* of the free electrons in the conductor. Effectively, these forces add together, and the effect is an emf generated, or *induced*, in the conductor. The direction of the induced emf depends on the direction of motion of the conductor relative to the direction of the magnetic field, and can be found by using the *right-hand rule*, which you studied in Volume 1. The right-hand rule states that if the thumb, forefinger, and middle finger of the right hand are held at right angles to one another, with the thumb pointing in the direction in which the conductor is moving and the forefinger pointing in the direction of the magnetic field, then the middle finger points in the direction of the induced emf.

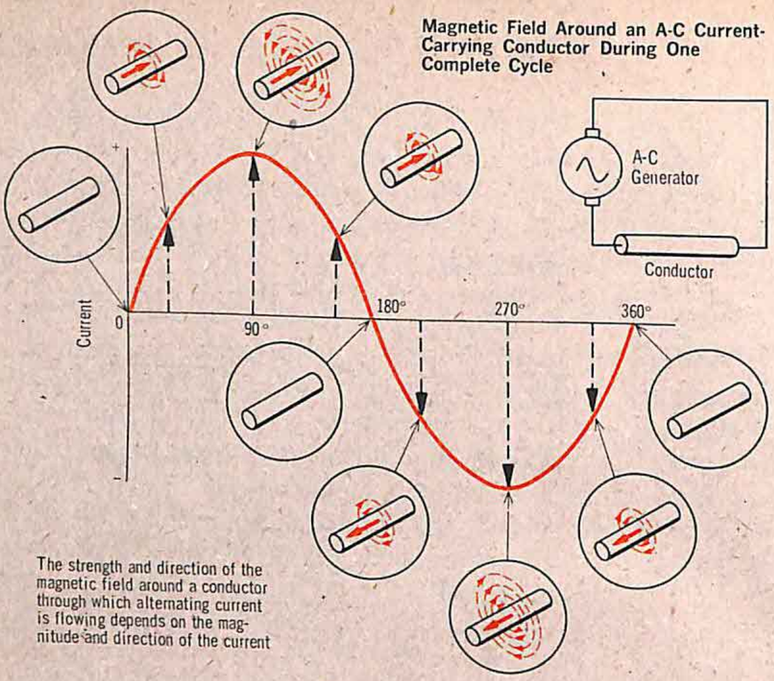


The magnitude of the induced emf is *directly proportional* to the strength of the magnetic field, the length of the conductor, and the speed at which the conductor moves through the magnetic field. Increasing any of these three factors will cause an increase in the induced emf. The magnitude of the induced emf also depends on the direction in which the conductor moves through the field. If the conductor moves at right angles to the direction of the field, the emf is maximum. If the direction of the conductor is parallel to the direction of the field, no emf is induced. See illustration on page 3-45. And if the conductor moves neither at a right angle nor parallel to the direction of the field, the emf is proportional to the sine of the angle between the direction of the field and the direction of motion of the conductor.

The above description was for the case of a *moving conductor* in a *stationary magnetic field*. As you will learn later, exactly the same results can be obtained by having a *moving magnetic field* and a *stationary conductor*.

factors determining induced emf




Magnetic Field Around an A-C Current-Carrying Conductor During One Complete Cycle
A-C Generator
Conductor
Current
+
0
–
90°
180°
270°
360°

The strength and direction of the magnetic field around a conductor through which alternating current is flowing depends on the magnitude and direction of the current

the magnetic field created by an alternating current

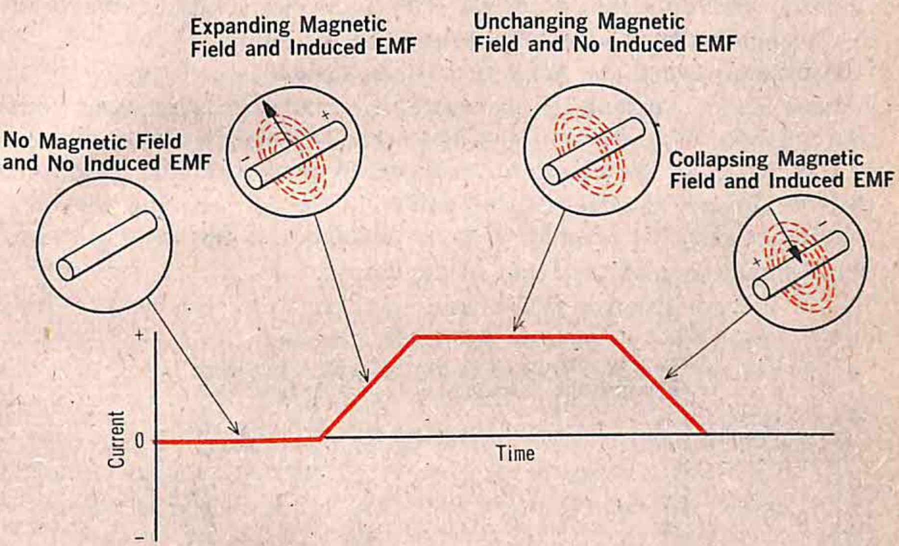
When a d-c voltage is applied to a conductor, the current goes from zero to its maximum value almost instantly. The magnetic field around the conductor also goes from zero to its maximum strength almost instantly, and *stays* at this strength as long as the *current flows*. When the circuit is opened, the current drops to zero, and the magnetic field around the conductor also decreases to zero. Usually, you picture the decrease of a magnetic *field* as the *collapse* of the lines of force back into the electrons that produced them.

When an alternating current flows in a conductor, the current constantly varies in magnitude. This means that the number of free electrons moving in the same direction also varies. As a result, the magnetic field around the conductor *constantly changes* in *strength*. The greater the current, the stronger is the field. Similarly, the less the current, the weaker is the field.

Since alternating current periodically changes direction, the magnetic field it produces also reverses direction. At any instant, the direction of the magnetic field is determined by the direction of current flow.

self-induction

As the alternating current in a conductor goes through one complete cycle, the magnetic field around the conductor builds up and then collapses. It then builds up in the opposite direction, and collapses again. When the magnetic field begins building up from zero, the lines of force, or *flux lines*, expand from the center of the conductor outward. As they expand outward, they can be thought of as cutting through the conductor. Remember that an emf is induced in any wire that moves in a magnetic field. In this case, it is the *field* that moves, but the effect is the same as if the wire was moving and the field was stationary. All that is required is relative motion between the magnetic field and the electron. Therefore, as the magnetic field expands outward through the conductor, it tends to produce a current flow of its own. Similarly, when the magnetic field collapses, the flux lines cut through the conductor again, and again an emf is induced.


Expanding Magnetic Field and Induced EMF
Unchanging Magnetic Field and No Induced EMF
No Magnetic Field and No Induced EMF
Collapsing Magnetic Field and Induced EMF
+
-
+
-
+
0
-
Current
Time

Any change in the current through a conductor causes self-duced emf in the conductor. If the current is zero or constant, no emf is induced

You can see then that any change in current causes an expansion or collapsing of the magnetic field around a conductor, which in turn induces an emf in the conductor. This is called *self-induction*.

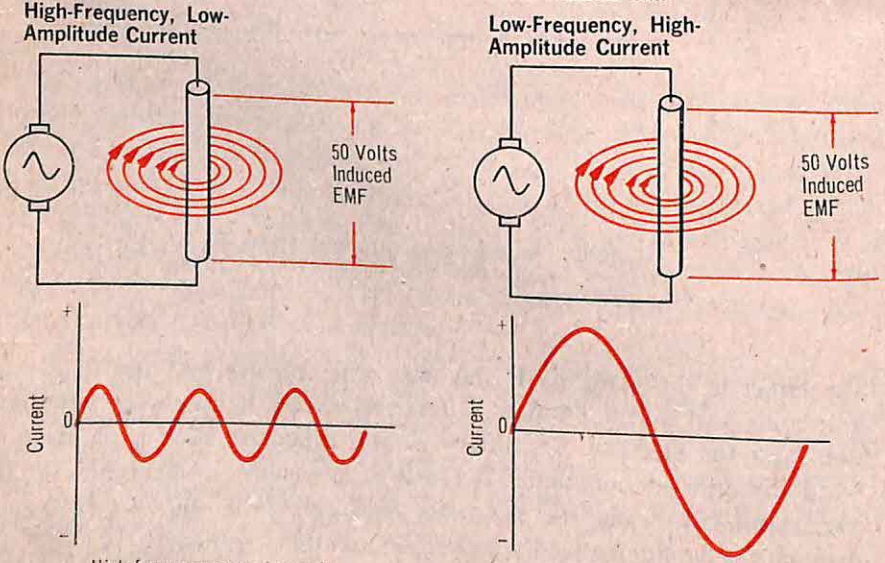
magnitude of self-induced emf

The emf induced in a conductor by a change in the current through the conductor has *magnitude* and *polarity,* the same as all emf's. One factor that determines the magnitude of the induced emf is the rate at which the magnetic field expands or collapses. This, in turn, depends on how rapidly the current changes. For pure alternating current, which varies as a sine wave, the *frequency* is a measure of how fast the current changes. Therefore, the magnitude of the induced emf depends on the frequency of the current. For a given value of current, the higher the frequency, the more rapidly the current changes, and thus the larger the emf induced. Similarly, the lower the frequency, the smaller will be the induced emf.

The magnitude of the induced emf also depends on the value of the *current.* Larger currents produce stronger magnetic fields. And when a strong field collapses, more flux lines cut the conductor, and a greater emf is induced. Therefore, for a given frequency, higher amplitude currents produce greater induced emf's.

Summarizing, the magnitude of the self-induced emf is proportional to the amplitude and frequency of the current.

The frequency of an a-c current and its amplitude determine the magnitude of the self-induced emf


High-Frequency, Low-Amplitude Current
50 Volts Induced EMF
Low-Frequency, High-Amplitude Current
50 Volts Induced EMF
+
Current
0
-
+
Current
0
-

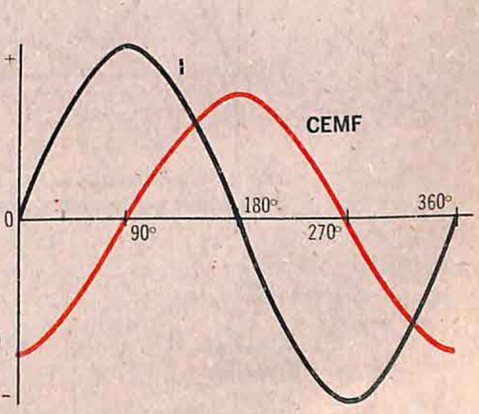
High-frequency currents can induce large emf's even though their amplitudes are relatively low

And low-frequency currents can also induce high emf's if their amplitudes are high

polarity of self-induced emf

Every emf has a polarity, and a self-induced emf is no exception. You might think that the polarity of an induced emf should always be in the same direction as the current that causes it. However, if you think in terms of a direct current flowing in a conductor, you will see that this cannot be so. When a direct current increases from zero to its maximum value, the magnetic field it creates around the conductor induces an emf in the conductor. If this emf was in the same direction as the current, it would cause an increase in the current. This increase in current would cause more induced emf, which would increase the current further. This sequence would continue until so much current flowed that something in the circuit would burn out. You know that this does not happen, and so the polarity of the induced emf is not always in the same direction as the current that causes it. The polarity of an induced emf is given by the right-hand rule, but this is hard to visualize when you are dealing with *self-induction*.

The direction of the self-induced emf was first explained by the German physicist H. F. E. Lenz, in what is now called *Lenz's Law: A change in current produces an emf whose direction is such that it opposes the change in current.* In other words, when a current is decreasing, the induced emf is in the same direction as the current and tries to keep the current from decreasing. And when a current is increasing, the polarity of the induced emf is opposite to the direction of the current and tries to prevent the current from increasing. The relationship between the induced emf and the applied voltage that causes the current flow is such that the two voltages are always *180 degrees out of phase.*



The magnitude of the cemf induced at any point depends on the rate of change of the flux lines. So, at 90 and 270 degrees, where I momentarily becomes steady at its peak, the rate of change is zero, and so is the cemf

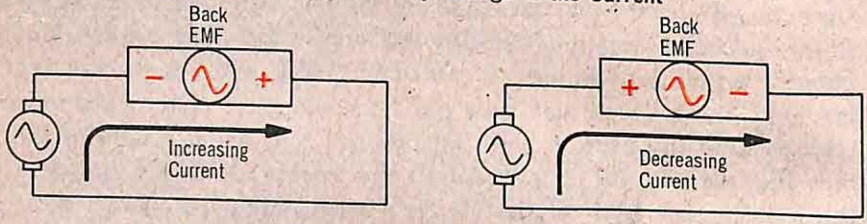
At 0, 180, and 360 degrees, when I passes through zero and changes direction, the rate of change is greatest, and so is the cemf. So I and cemf are 90 degrees out of phase

polarity of self-induced emf (cont.)

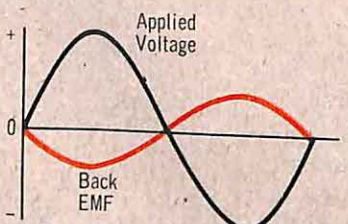
When the applied voltage is at its maximum in one direction, the induced emf is at its maximum in the opposite direction. And when the applied voltage is increasing or decreasing in one direction, the induced emf is increasing or decreasing in the opposite direction. Since the action of the induced emf is to oppose the applied voltage, it is often called the *back emf* or *counter emf*, and is generally abbreviated as *cemf*.

The fact that the back emf always opposes the applied voltage, but sometimes opposes and sometimes aids the current flow may seem confusing. This seeming contradiction is caused by the phase relationship between the applied voltage and the current, and will be explained later in this volume.

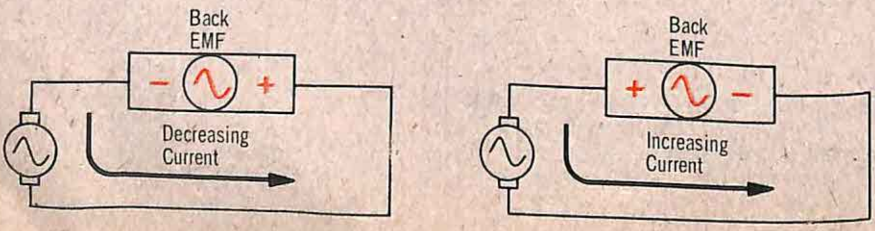
The Back EMF Opposes Any Change in the Current



The polarity of the back emf is opposite to the circuit current when current is increasing, and the same as the circuit current when current is decreasing



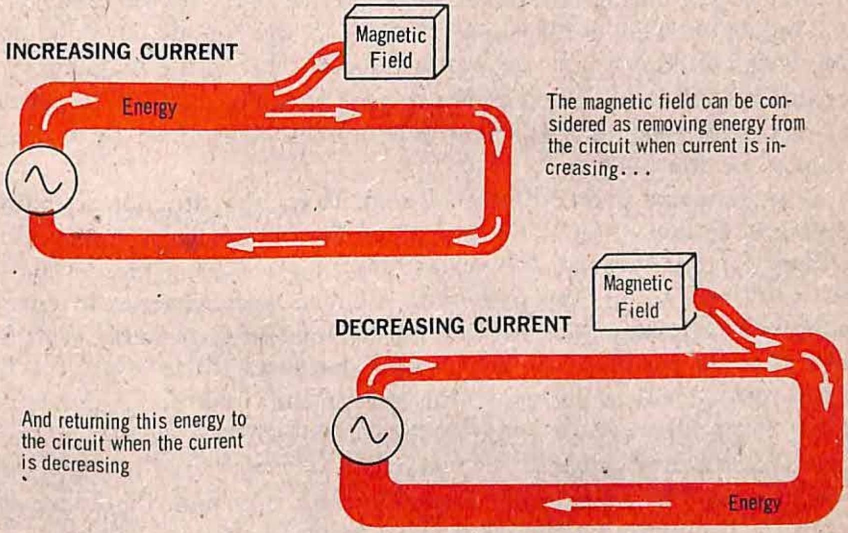
The back emf always opposes the applied voltage. Back emf is also known as counter emf or cemf



self-induction from an energy standpoint

Self-induction can also be explained from the standpoint of *energy*. When this is done, the magnetic field that surrounds a current-carrying conductor is considered as *exchanging* energy with the circuit. When circuit current *increases*, energy is *removed* from the circuit and stored in the magnetic field. This is why the magnetic field becomes stronger. The removal of circuit energy shows up as a decrease in the potential along the conductor, and corresponds to the back emf opposing the source voltage.

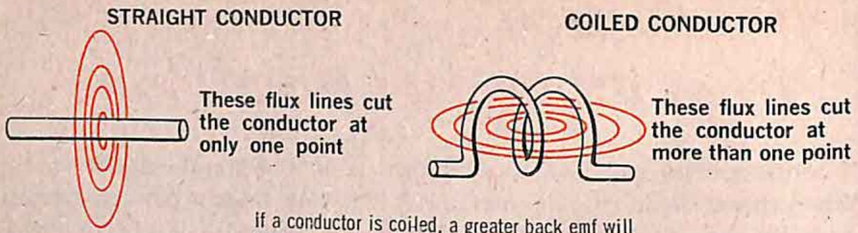
When current stops increasing, the magnetic field becomes constant and stops removing energy from the circuit; and all of the energy supplied by the power source is used by the circuit current. The magnetic field holds all of the energy it has taken from the circuit until the current begins *decreasing*.



The magnetic field can be considered as removing energy from the circuit when current is increasing. . .

And returning this energy to the circuit when the current is decreasing

When the current starts decreasing, the magnetic field starts collapsing and returns the stored energy to the circuit. It returns the energy in the form of increased potential along the conductor. This corresponds to the self-induced emf being in the same direction as the source voltage, and thus adding to it. From the energy standpoint, therefore, self-induction is a removal of energy from a circuit when current increases, and a returning of this energy to the circuit when current decreases.


STRAIGHT CONDUCTOR
These flux lines cut the conductor at only one point
COILED CONDUCTOR
These flux lines cut the conductor at more than one point

If a conductor is coiled, a greater back emf will be produced by self-induction

effect of conductor shape on self-induction

You now know that self-induction in a conductor opposes any change in the current through the conductor, and that the amount, or magnitude, of the self-induction is determined by the amplitude and frequency of the current. However, there is one other factor that affects self-induction. This is the *physical shape* of the conductor. Until now, you have considered only *straight* conductors. When the magnetic field in this type of conductor builds up, each flux line cuts the conductor in one place, and the back emf produced is determined by the total number of flux lines.

If a conductor is *coiled*, into adjacent loops, the situation is entirely different. For one thing, the length of the conductor is longer, so a greater cemf is induced. But, in addition, there is another reason why the cemf will go up even more with a coiled wire. Changes in current still produce a magnetic field around the conductor, but now each flux line does not cut the conductor at only one point. First of all, the flux lines add to create a stronger field, and as each flux line expands outward, it cuts the conductor in the loop in which it is produced, and it also cuts *adjacent loops* of the conductor. The more the flux lines add and expand, the more loops they cut. Each flux line, therefore, generates a back emf at more than one point along the conductor. The polarity of all these back emf's are such that they *add* to produce a total counter emf much greater than would be generated in a straight conductor by the same change in current. When the flux lines collapse, the situation is the same. Each line cuts more than one loop of the conductor, and generates a cemf in every loop it cuts. The cemf's again add to produce a large total back emf.

You can see that for a given current, the amount of back emf produced in a conductor depends on the number of individual flux lines generated, the shape of the conductor, and the frequency of the current.

summary

☐ If either inductance or capacitance is present in an a-c circuit, the current flow is limited. ☐ An induced emf is developed when a conductor cuts magnetic lines of force. Either a moving conductor in a stationary magnetic field, or a moving magnetic field and a stationary conductor will produce an induced emf.

☐ When a varying current flows in a conductor, it creates a magnetic field which induces an emf in the conductor. This is self-induction. ☐ The magnitude of the self-induced emf is proportional to the amplitude and frequency of the current. ☐ The direction of a self-induced emf is explained by Lenz's Law. Lenz's Law states: A change in current produces an emf whose direction is such that it opposes the change in current. ☐ Self-induced emf is sometimes called back emf, or counter emf, and is abbreviated cemf.

☐ Self-induction can be considered an exchange of energy when the magnitude of the current through a conductor changes. ☐ The physical shape of a conductor also determines the magnitude of self-induction. ☐ Conductors are sometimes coiled to increase the number of flux lines cut by the conductor, and this results in larger self-induced emf.

review questions

1. What properties, in addition to resistance, limit the current in an a-c circuit?
2. What rule gives the direction of the magnetic field around a current-carrying conductor? State the rule.
3. For a conductor moving through a magnetic field, what rule gives the direction of the induced emf when the direction of the magnetic field is known? State the rule.
4. What factors determine the magnitude of the induced emf?
5. What is *self-induction*?
6. On what two factors does the magnitude of a self-induced emf depend?
7. What is mean by *counter emf*? By *back emf*?
8. State Lenz's Law.
9. What determines the direction of the self-induced emf? How does Lenz's Law explain this?
10. How can self-induction be explained from an energy standpoint?

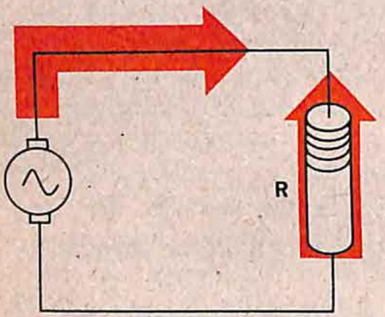
inductance

Since, for a given amplitude and frequency of current, the back emf developed in a conductor depends on the shape of the conductor, the exact relationship between the current, back emf, and the shape of the conductor can be expressed mathematically: When the number of flux lines produced by the current is multiplied by a constant that is determined by the shape of the coil, the product equals the back emf produced. The equation for this is

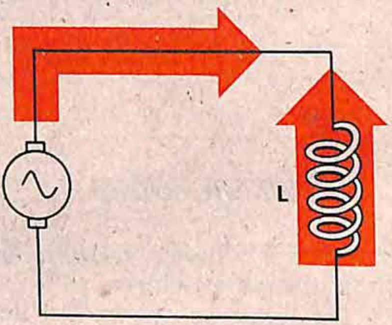
$$E_{cemf} = L \times \text{number of flux lines}$$

The constant, L, which depends on the conductor shape, is called the *inductance* of the conductor.

The inductance of *straight* conductors is usually *very low*, and for our purposes can be considered zero. The inductance of *coiled conductors*, though, can be *high*, and plays an important role in the analysis of a-c circuits.

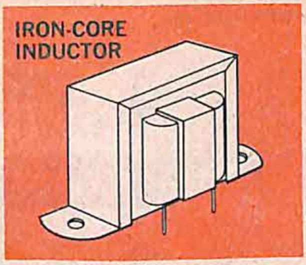


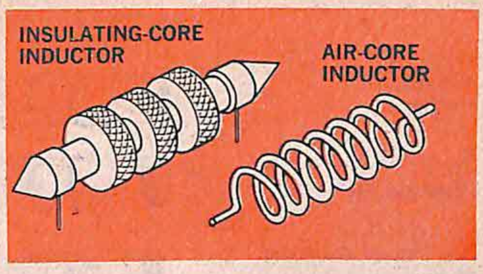
Resistors oppose all current in a circuit. They have resistance, which is abbreviated R

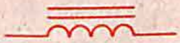


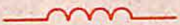
Inductors oppose changes in current in a circuit. They have inductance, which is abbreviated L

Although inductance is actually a physical characteristic of a conductor, it is often defined in terms of its effect on current flow. This definition of inductance is as follows: *Inductance is that property of an electrical circuit that tends to oppose any change of current through the circuit.* You can see from this definition that inductance has no effect on a steady d-c current. It only opposes changes in current. Coiled conductors are usually used in a-c circuits to deliberately introduce inductance into the circuit. Such a coiled conductor is called an *inductor*.






This is the symbol for an iron-core inductor

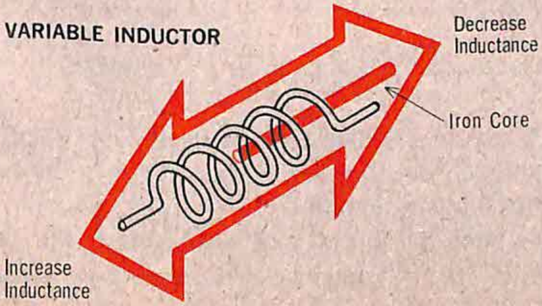

This is the symbol for an insulating-core inductor or an air-core inductor

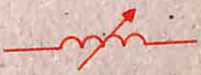
inductors

Basically, all inductors are made by winding a length of conductor around a core. The conductor is usually solid copper wire coated with enamel insulation; and the core is made either of magnetic material, such as powdered iron, or of insulating material. When an inductor is wound around an insulating core, the core is used only for a support, since it has no magnetic properties. If heavy wire is used in making the inductor, a core is actually not needed; the rigid loops of wire support themselves. When a magnetic core is not used, the inductor is usually referred to as an *air-core inductor*.

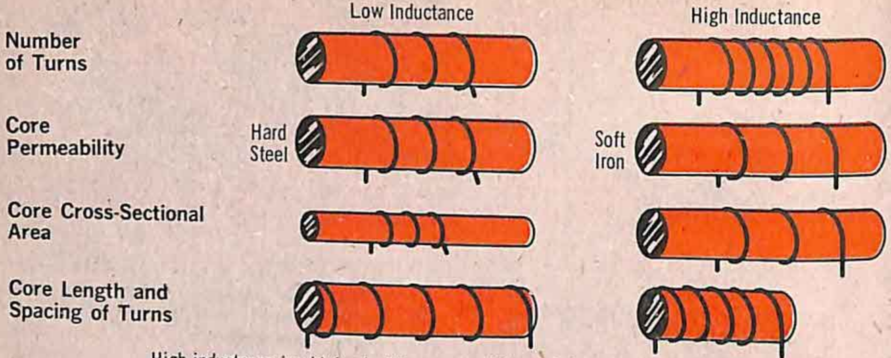
Inductors with set values of inductance that cannot be changed are called fixed inductors. Inductors whose inductance can be varied over some range are called variable inductors. Usually, variable inductors are made so that the core can be moved into and out of the winding. The position of the core then determines the inductance value.

Inductors are also frequently called *chokes* or *coils*. All three of these terms mean the same thing, and you should be familiar with each of them.




This is the symbol for a variable inductor

FACTORS AFFECTING INDUCTANCE



High inductance is obtained with a reasonably small inductor by winding the wire around the core in many layers

factors determining inductance

The physical characteristics, or geometry, of both the *core* and the *windings* around the core affect the inductance produced. Inductors with *magnetic cores* have much greater inductances than those with *insulating* or *air* cores. The reason is that all of the flux lines produced by an inductor pass through the core, and in doing so, magnetize the core, if it is made of magnetic material. The flux lines of the magnetic field of the core then *add* to and *strengthen* the flux lines created by the winding, and therefore, a greater cemf is produced. For a given number of turns in the inductor winding, a core with a *larger cross-sectional area* will produce more flux lines. Also, the *longer* the core is for a given number of turns, the *less* flux lines it will produce. The inductance, therefore, is directly proportional to the cross-sectional area of the core, and inversely proportional to its length.

The number and spacing of the individual turns of wire in an inductor also greatly affect the inductance. The *more turns* there are, the *greater* is the inductance. And the *closer together* they are, also the greater is the inductance. The relationships between inductance and all the physical factors that affect it are expressed by the equation:

$$L = \frac{0.4\pi N^2 \mu A}{l}$$

where N is the number of turns; μ is the core permeability, which is high for magnetic materials and low for other materials; A is the core cross-sectional area; and l is the core length.

For every magnetic core material there is a point where the core becomes *saturated;* then even large changes in current cannot increase flux, and very little cemf is produced.

inductance values and cemf

Inductance is actually a measure of how much counter emf is generated in a circuit or component for a certain change in current through that circuit or component. In other words, it is the amount of cemf produced for a unit change of current. The unit of inductance is the *henry*, named in honor of the American physicist Joseph Henry, who shares the honor of the discovery of induction with Michael Faraday. The henry is defined as follows: *A conductor or coil has an inductance of one henry if a current that changes at the rate of one ampere per second produces a cemf of 1 volt.* Therefore, the greater the inductance, the greater the henrys. The abbreviation for the henry is *h*.

The henry is a fairly large unit. For this reason, inductance is often given in the smaller units of the millihenry and the microhenry. One millihenry is 1/1000 of a henry, and one microhenry is 1/1,000,000 of a henry. The millihenry is abbreviated *mh;* the microhenry *μh*.

Since the amount of cemf produced is part of the definition of the henry, you can actually calculate the cemf that an inductor generates in a circuit when you know its *inductance* value, and the *amplitude* and *frequency* of the current. One form of the equation for cemf is

$$\text{cemf} = -L(\Delta I/\Delta t)$$

The minus sign indicates that the cemf is opposite in polarity to the applied voltage. The ΔI term, pronounced "delta I," is the change in current that takes place in a time of Δt, which is the change in time. As an example of the use of the equation, consider the cemf developed by an inductor having an inductance of 10 henrys when the current changes from 5 to 3 amperes in 1 second.

$$\text{cemf} = -L\frac{\Delta I}{\Delta t} = -10\left(\frac{5-3}{1}\right) = -20 \text{ volts}$$

You can see that by changing either the inductance (L) or the rate of change of the current (ΔI/Δt), which is the frequency, various values of cemf can be obtained. The table below shows how the cemf would rise as the rate of change of the current was increased.

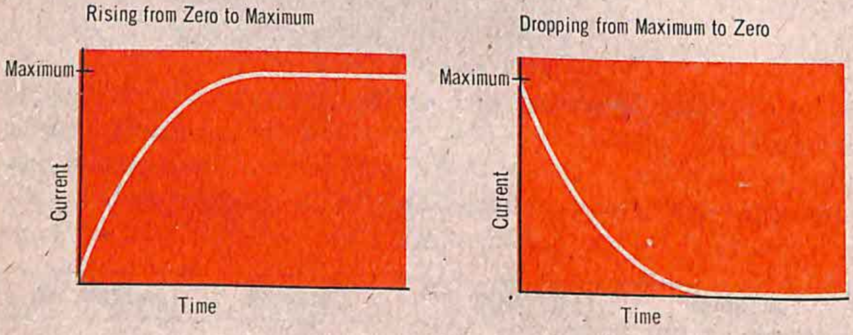
L (HENRYS)	I (AMPERES)	t (SECONDS)	cemf (VOLTS)
1	1	1	1
1	1	1/2	2
1	1	1/4	4
1	1	1/10	10
1	1	1/20	20
1	1	1/50	50
1	1	1/100	100
1	1	1/500	500
1	1	1/1000	1000

inductive d-c circuits

In a d-c circuit, the only *changes* in current occur when the circuit is closed and when it is opened. If the circuit contains only resistance, these changes can be considered as *instantaneous*. Thus, when the circuit is closed, the current instantly increases from zero to its maximum value. And when the circuit is opened, the current instantly drops to zero. If inductance is added to a d-c circuit, say in the form of an inductor, the current can no longer change instantly. When the circuit is closed, the current tries to increase instantly, but is opposed by the back emf generated by the inductor. So instead of increasing instantly, it takes a definite amount of time for the current to reach its maximum value. The greater the inductance, the larger is the back emf produced, and so the longer it takes the current to reach its maximum.

The situation is identical when the circuit is opened and the current tries to decrease to zero instantly. The back emf opposes the change, and so the current decreases to zero gradually. The waveform of any d-c current change through an inductor has the same *basic shape*, regardless of the values of current and inductance. This waveform shows that the current changes rapidly at first, and then gradually changes less and less; until it reaches its maximum value if it is an increasing current, or zero if it is a decreasing current. Because of its shape, this waveform is called an *exponential* waveform, or curve.

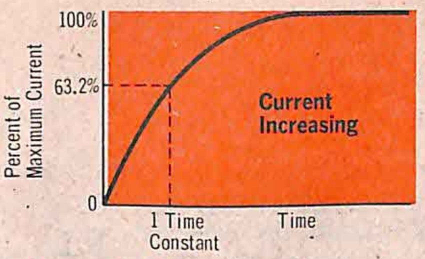
D-C Current Through an Inductance



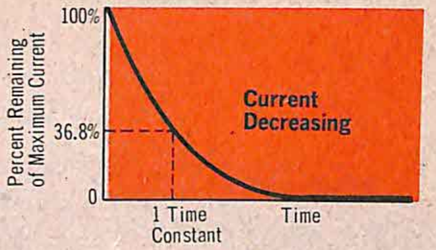
In a d-c circuit containing inductance, the current follows an exponential waveform when it changes from zero to maximum (circuit closed)

The current follows an exponential waveform when it changes from maximum to zero (circuit opened)

At all times when the current is not changing, the inductance has no effect on the circuit



In 1 time constant the current increases from zero to 63.2% of its maximum value



In 1 time constant the current falls 63.2% from its maximum value, leaving 36.8%

inductive time constant

In a d-c circuit containing inductance as well as resistance, the current changes gradually between zero and maximum, and between maximum and zero. Regardless of the values of inductance and resistance in the circuit, these changes always follow a *similar* pattern. Initially, the change is greatest, and then it gradually tapers off until the current reaches its constant value, which is either its maximum or zero. During these changes, a relationship exists between the *values* of current reached, and the *time* it takes to reach them. This relationship is expressed by a quantity called the *time constant*.

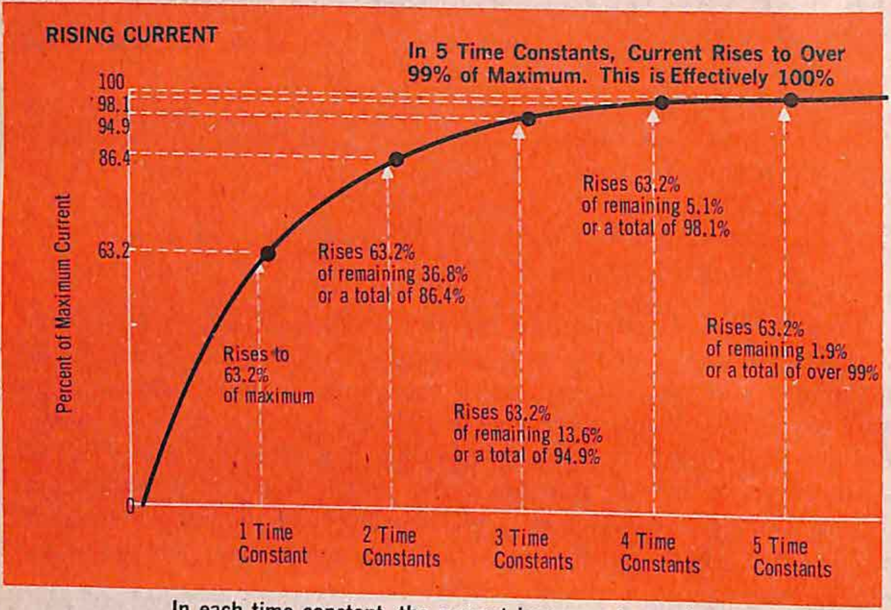
The time constant is defined as the time required for the current to either increase to 63.2 *percent* of its maximum value, or to decrease 63.2 percent from its maximum value. In any d-c circuit, the time constant depends on the value of the *inductance* and the *resistance*. The value of the time constant is directly proportional to the inductance and inversely proportional to the resistance. If these two quantities are known, the time constant can be calculated from the equation

$$\text{Time constant} = \text{inductance}/\text{resistance} \qquad \text{or} \qquad t = L/R$$

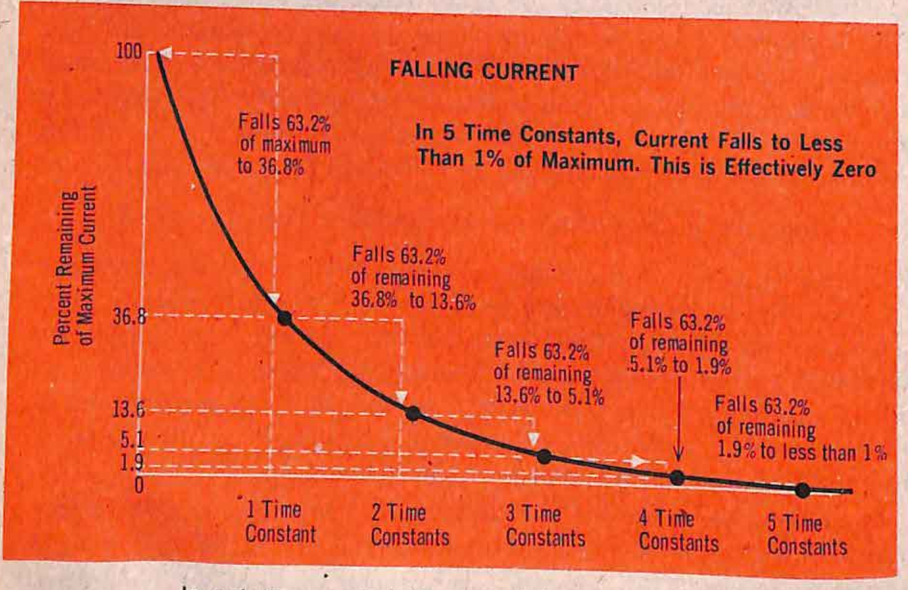
With this equation, if the inductance is in henrys and the resistance in ohms, the time constant will be in seconds. In actual practice, time constants are usually very short. For this reason, they are often expressed in *milli*seconds and *micro*seconds, where one millisecond is one one-thousandth (1/1000) of a second, and one microsecond is one-millionth (1/1,000,000) of a second. Millisecond is often abbreviated *millisec*, and microsecond is abbreviated *μsec*.

Once the time constant for a circuit is known, you can easily figure how long it takes for the current to go from zero to maximum, or from maximum to zero. This is because, as you can see from the illustration on page 3-60, it takes a time equal to five time constants for the current to rise to its maximum or drop to zero.

rising and falling currents



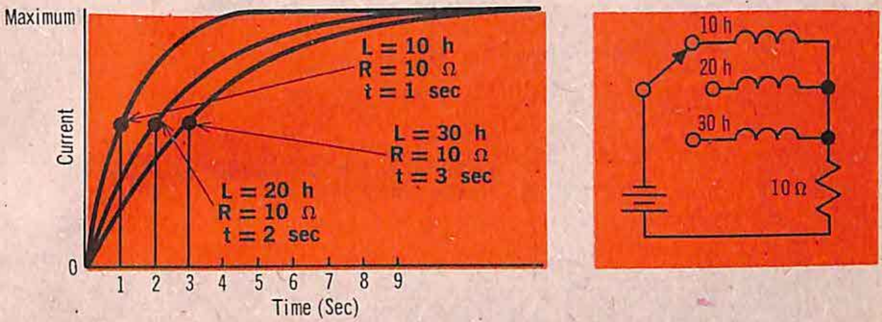
In each time constant, the current increases to a value 63.2% closer to its maximum value



In each time constant, the current decreases to a value 63.2% closer to zero

effect of increasing or decreasing inductance

The amount of inductance in a d-c circuit determines *how long* it takes the current to build up to its maximum value when the circuit is closed, as well as how long it takes the current to drop to zero when the circuit is opened. If there is no inductance in the circuit, the current changes are for all practical purposes *instantaneous*. The effect of adding inductance is to create a *delay* in the time it takes the current to change. The more inductance added, the longer it takes the current to change. The exact relationship between the inductance and the time required to change is given by the equation for the inductive time constant, $t = L/R$. For example, if the resistance of a circuit is 10 ohms and the inductance is 2 henrys, the circuit time constant is



Increasing the inductance in a d-c circuit increases the circuit time constant, and, therefore, increases the time it takes the current to change between its zero and maximum values

$$t = L/R = 2 \text{ henrys}/10 \text{ ohms} = 0.2 \text{ second}$$

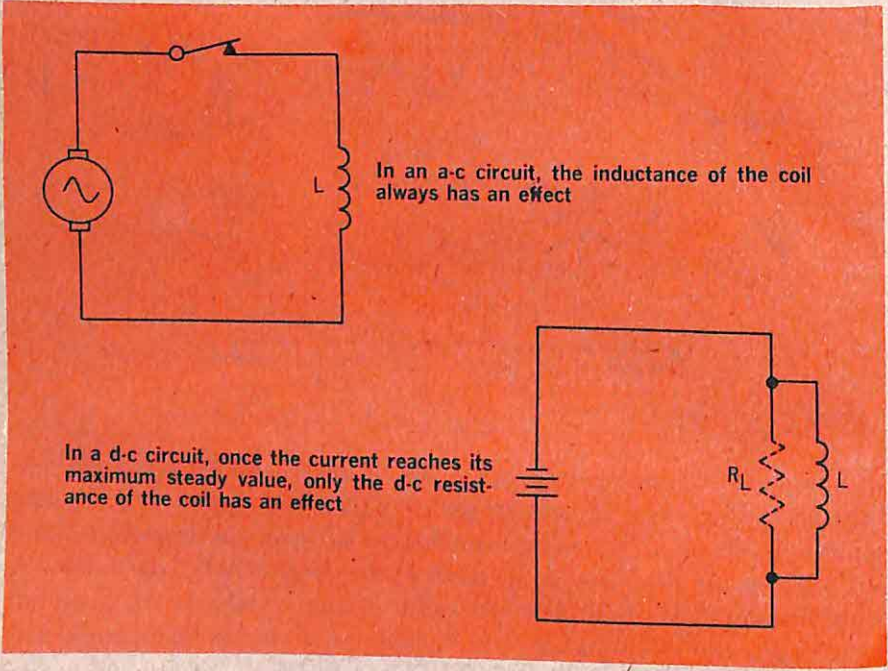
And since the current changes from zero to maximum or vice versa in 5 time constants, it takes 5×0.2 second, or 1 second, for such a change. If the inductance is increased to 4 henrys, the circuit time constant becomes

$$t = L/R = 4 \text{ henrys}/10 \text{ ohms} = 0.4 \text{ second}$$

And 5 time constants equal 5×0.4 second, or 2 seconds. Thus, doubling the inductance, doubles the time it takes the current to change between its two values. Similarly, if the inductance is tripled, the time will be tripled. And if the inductance is cut in half, the time will also be halved.

inductive a-c circuits

Unlike a d-c circuit, in which the current only changes when the circuit is opened and when it is closed, in an a-c circuit the current changes *frequently*. For *sinusoidal-type ac*, the current changes almost constantly, varying in magnitude continuously, and reversing direction periodically. Since this is the most common type of ac, and the type which forms the basis of a-c circuit theory, the rest of this volume will apply to ac that varies as a sine wave, unless otherwise stated.



In an a-c circuit, the inductance of the coil always has an effect

In a d-c circuit, once the current reaches its maximum steady value, only the d-c resistance of the coil has an effect

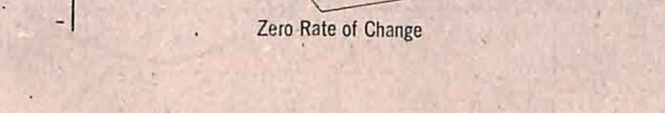
Inductance affects the operation of pure d-c circuits only at the instant they are opened and the instant they are closed. In an a-c circuit, on the other hand, the current is always changing, and the inductance is always opposing the change. The inductance, therefore, has a *constant* effect on circuit operation. Thus, from the time the switch in the circuit is closed until it is opened again, inductance affects the circuit operation.

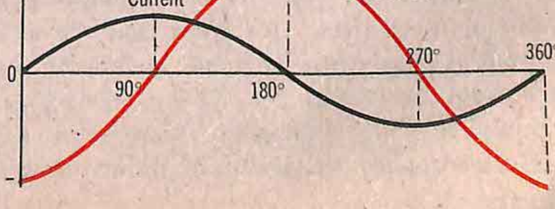
The circuit shown contains only inductance. Actually, this can never be, since the source, the connecting wires, and the inductor all must have some resistance. However, if these resistances are very small and have a much smaller effect on the circuit current than does the inductance, the circuit can be considered as containing only inductance.

a-c voltage and current relationships

In any a-c circuit that contains only inductance, there are three varying quantities with which you will normally be interested. These are (1) the applied voltage, (2) the induced back emf, and (3) the circuit current. You will remember that if an a-c circuit has only *resistance*, the voltage and current in the circuit are in phase. If the circuit has inductance instead of resistance, this is no longer true. The back emf and time delay generated by the inductance destroys the in-phase relationship between the applied voltage and the circuit current. The applied voltage and the current are, therefore, out of phase. Furthermore, the back emf is out of phase with both the applied voltage and the current.

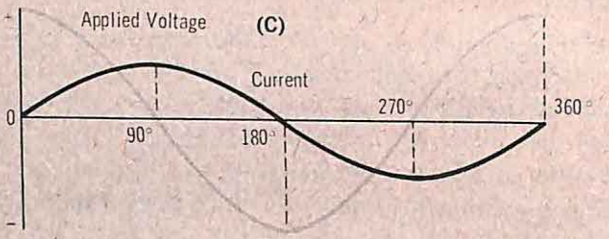
The phase relationships in an inductance can most easily be understood by considering first the current and the back emf. You know two things about the current and the back emf. One is that the cemf is maximum when the *rate of change* of current is the greatest, and is zero when the current is not changing. The reason for this is that when the current changes rapidly, the flux lines expand or collapse rapidly, and so there is a greater relative motion between the conductor and the magnetic field. The second relationship is that the direction of the cemf is such that it always opposes the current change.

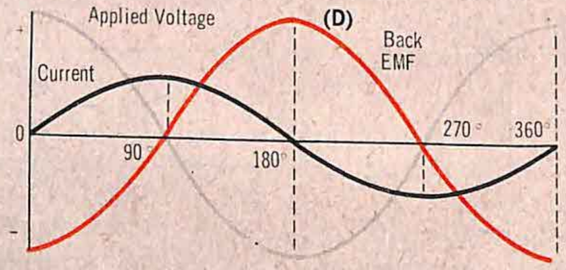




a-c voltage and current relationships (cont.)

Waveform A, on page 3-63, shows one cycle of a-c current. The rate of change is greatest where the slope of the waveform is greatest. You can see that this occurs at those points where the waveform passes through zero; or at 0, 180, and 360 degrees. This means that the most cemf is generated at 0, 180, and 360 degrees, as shown on the waveforms in B on page 3-63. Around 90 and 270 degrees, the current changes very little; as a matter of fact, at exactly 90 and 270 degrees, where the current changes from rising to falling, the current is momentarily steady. Therefore, the flux lines do not change at those points, and no cemf is induced. Since at 0 degrees the current is passing through zero in a positive direction, the cemf must be maximum in the negative direction, inasmuch as it always opposes the increase in current. Similarly, when the current begins to decrease, at 90 degrees, the cemf must be increasing in the positive direction to aid the current flow. As shown, therefore, the cemf follows *Lenz's Law* by lagging the current by 90 degrees. You know that the applied voltage is 180 degrees out of phase with the cemf, and so the applied voltage must lead the current by 90 degrees. This is shown on the waveforms in C on this page. The relationships between all three quantities (current, cemf, and applied voltage) are shown on the waveforms in D on this page.





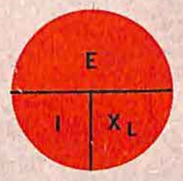
In an inductance: (1) the applied voltage leads the current by 90°; (2) the back emf lags the current by 90°; and (3) the applied voltage and the back emf are 180° out of phase

inductive reactance

In a d-c circuit with a fixed applied voltage, the amount of current that flows depends on the resistance of the circuit, which opposes the flow of current. In an a-c circuit that has only resistance, the same is true. But, in an a-c circuit that only has inductance, the amount of current that flows is determined by the cemf, which counteracts the applied voltage to oppose current flow. The cemf acts just like a resistance to limit current flow. But cemf is discussed in terms of volts, so it cannot be used in Ohm's Law to compute current. However, the effect of cemf can be given in terms of ohms. This effect is called *inductive reactance*, and is abbreviated X_L. Since the cemf generated by an inductor is determined by the inductance (L) of the inductor, and the frequency (f) of the current, the inductive reactance must also depend on these things. The inductive reactance can be calculated by the equation:

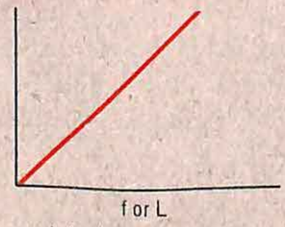
$$X_L = 2\pi fL$$

where X_L is the inductive reactance, in ohms; the value of 2π is approximately 6.28; f is the frequency of the current, in cycles per second; and L is the inductance, in henrys. The quantity $2\pi f$ together actually represents the *rate of change* of the current.

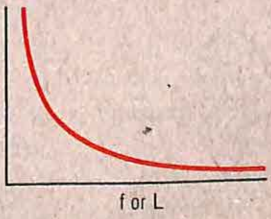


In a purely inductive circuit, inductive reactance has the same effect as resistance in either a d-c circuit or an a-c resistive circuit

You can see from the equation that the higher the frequency or the greater the inductance, the more will be the inductive reactance. Likewise, the lower the frequency or the inductance, the smaller will be the inductive reactance.



Inductive reactance changes linearly with frequency and inductance



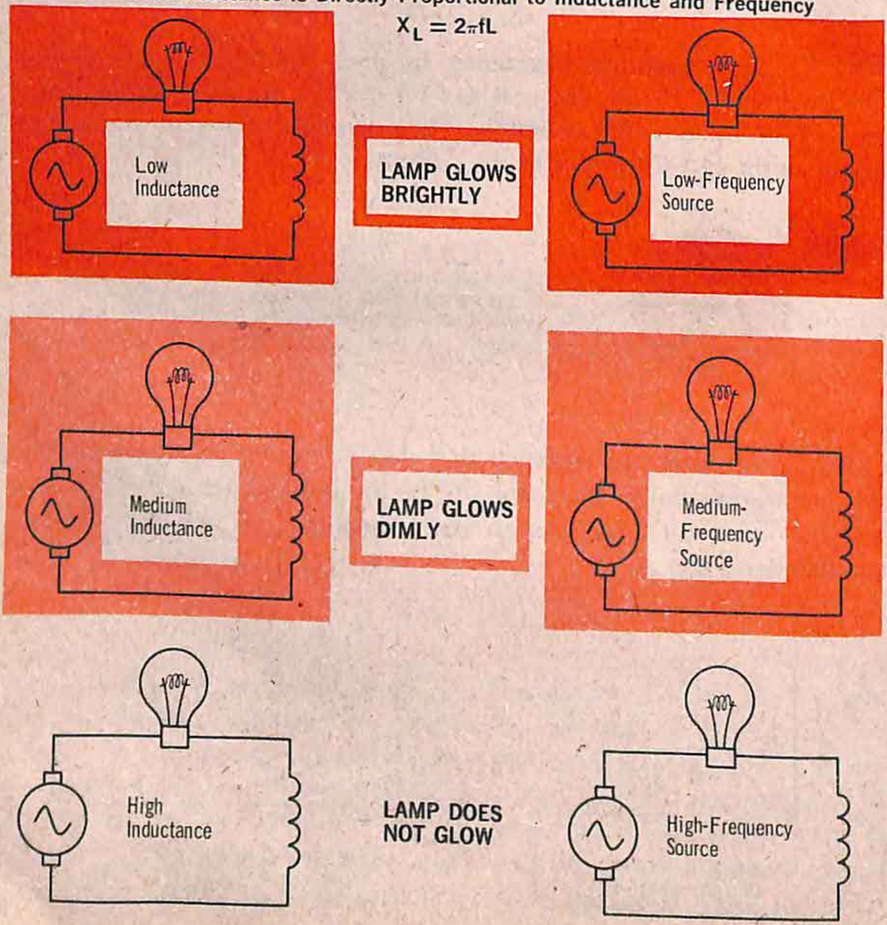
The current through an inductance changes nonlinearly with frequency

inductive reactance (cont.)

In a-c circuits that contain only inductance, the inductive reactance is the only thing that limits current flow. Such circuits can be solved by Ohm's Law merely by using the inductive reactance in place of the resistance. Therefore, $I = E/X_L$. An important difference, though, is that a particular value of inductive reactance applies only to *one specific frequency*. Thus, if you calculated the inductive reactance in a circuit for a frequency of 30 cps and then used this value to find the circuit current, the result would hold only if the frequency was constant. If the frequency changed, the inductive reactance would change, and so also would the circuit current. With only resistance, as you know, the frequency has no effect on the basic resistance.

Inductive Reactance Is Directly Proportional to Inductance and Frequency

$X_L = 2\pi fL$



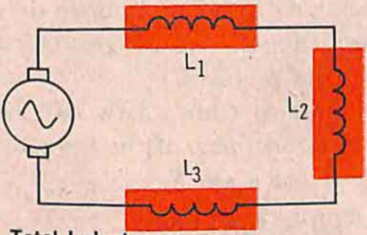
series and parallel inductors

To meet circuit requirements, it is frequently necessary to connect inductors in series or in parallel. When this is done the total inductance is calculated in exactly the *same way* as you calculate the *total resistance* of series and parallel resistors. For series inductors, this means that the total inductance is the *sum* of the *inductances* of the individual inductors. In the form of an equation, this is expressed as:

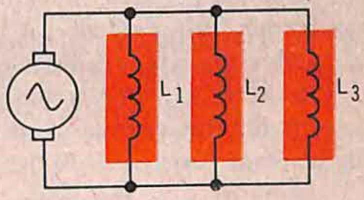
$$L_{TOT} = L_1 + L_2 + L_3 + \ldots + \text{etc.}$$

For parallel inductors, all of the methods described in Volume 2 for finding the effective resistance of parallel resistances can be used. The general method, which you remember applies in all cases, is the *reciprocal method*. For parallel inductors, this method is expressed as:

$$L_{TOT} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots + \text{etc.}}$$



Total Inductance:
$L_{TOT} = L_1 + L_2 + L_3$
Total Inductive Reactance:
$X_{L\,TOT} = X_{L1} + X_{L2} + X_{L3}$



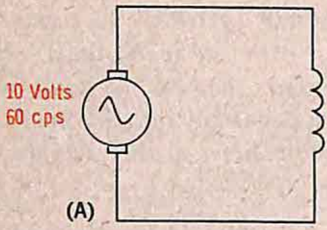
Total Inductance:
$$L_{TOT} = \frac{1}{\frac{1}{L_1}+\frac{1}{L_2}+\frac{1}{L_3}}$$
Total Inductive Reactance:
$$X_{L\,TOT} = \frac{1}{\frac{1}{X_{L1}} + \frac{1}{X_{L2}} + \frac{1}{X_{L3}}}$$

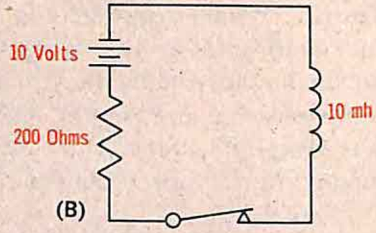
The total inductance or inductive reactance of series and parallel inductors is calculated the same as the total resistance of series and parallel resistance combinations

The total inductive reactance of series and parallel combinations of inductors can be found using the same methods used to find the total inductance. Or, the total inductive reactance can be found by first determining the total inductance and then calculating the total inductive reactance of this single inductance.

The methods just described for finding the total inductance of series and parallel inductors assume that the inductors are physically placed so that the flux lines from each inductor do not cut the windings of the other inductors. This cutting of the windings of one inductor by the flux lines of another is called *mutual induction*.

solved problems





Problem 5. In which of these circuits is the current the greatest?

In circuit B, the applied voltage is 10 volts and the total circuit d-c resistance is 200 ohms. Theoretically, the inductor has no effect on the d-c current once the current has reached its maximum, or steady-state value. You can, therefore, consider the 10-millihenry inductor as a short circuit to the d-c current since it has negligible resistance. The current in circuit B is calculated simply by Ohm's Law:

$$I = E/R = 10 \text{ volts}/200 \text{ ohms} = 0.05 \text{ ampere}$$

(In actual practice, inductors do have some d-c resistance, since they are made of turns of wire. A 10-mh inductor, though, can be considered as having an insignificant d-c resistance in the problem.)

Circuit A is a purely inductive circuit, and so Ohm's Law can be used to find the current by using the inductive reactance of the inductor in place of resistance. First, then, you must calculate X_L:

$$X_L = 2\pi fL = 6.28 \times 60 \text{ cps} \times 0.01 \text{ h} = 3.748 \text{ ohms}$$

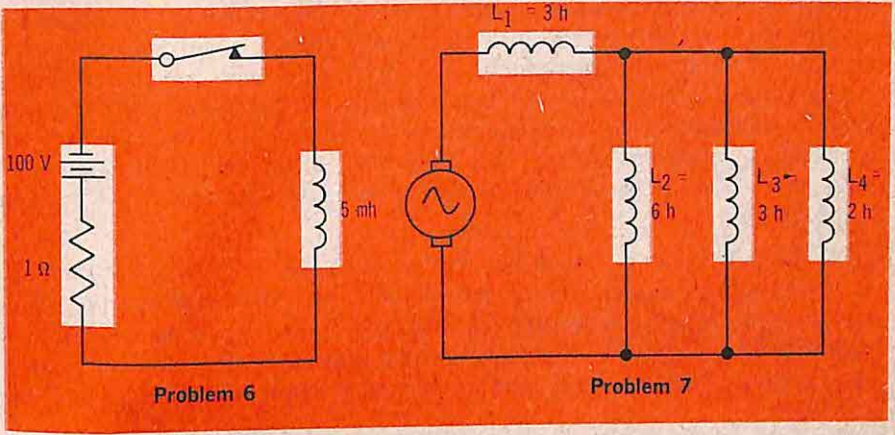
Notice that the inductance value of 10 mh was converted to the basic unit of the henry before the equation was solved. This must always be done. If the frequency had been given in kilocycles or megacycles, it also would have had to been converted to its basic unit (cps).

Once X_L is known, use Ohm's Law to find the circuit current. Actually, since you know the voltage applied to both circuits, and the opposition to current flow in each, you should realize that more current will flow in circuit A than in circuit B. This is obvious, inasmuch as Ohm's Law says that for the same voltage, less resistance will allow more current to flow. If you wanted to calculate the current in circuit A, though, it would be:

$$I = E/X_L = 10 \text{ volts}/3.75 \text{ ohms} = 2.66 \text{ amperes}$$

In the above problem, an important assumption was made that the 10 volts given for the source voltage of circuit A was an rms value. If it were not, the current in circuit A would bear no relationship to the current in B, and therefore the two currents could not be compared.

solved problems (cont.)



Problem 6. *How long will it take the current in the circuit to reach its full value?*

Once the switch is closed, it will take a time equal to 5 time constants for the current to reach its full value. One time constant, t, equals the inductance, in henrys, divided by the resistance, in ohms. Therefore,

$$t = L/R = 0.005 \text{ henry}/1 \text{ ohm} = 0.005 \text{ second}$$

Thus,

$$5t = 0.025 \text{ second}$$

Problem 7. *What is the total inductance in the circuit?*

A series-parallel combination of inductances is reduced to a single equivalent inductance, the same as a series-parallel combination of resistances would be reduced, by applying the reciprocal method.

$$L_{2\text{-}3\text{-}4} = \frac{1}{\frac{1}{L_2} + \frac{1}{L_3} + \frac{1}{L_4}} = \frac{1}{\frac{1}{6} + \frac{1}{3} + \frac{1}{2}}$$

$$= \frac{1}{\frac{1}{6} + \frac{2}{6} + \frac{3}{6}} = \frac{1}{\frac{6}{6}} = 1 \text{ henry}$$

This reduces the original circuit to two series inductances. The total circuit inductance is now found by simply adding L_1 and $L_{2\text{-}3\text{-}4}$.

$$L_{TOT} = L_1 + L_{2\text{-}3\text{-}4} = 3 + 1 = 4 \text{ henrys}$$

The total inductance of the four series-parallel inductances is, therefore, 4 henrys.

summary

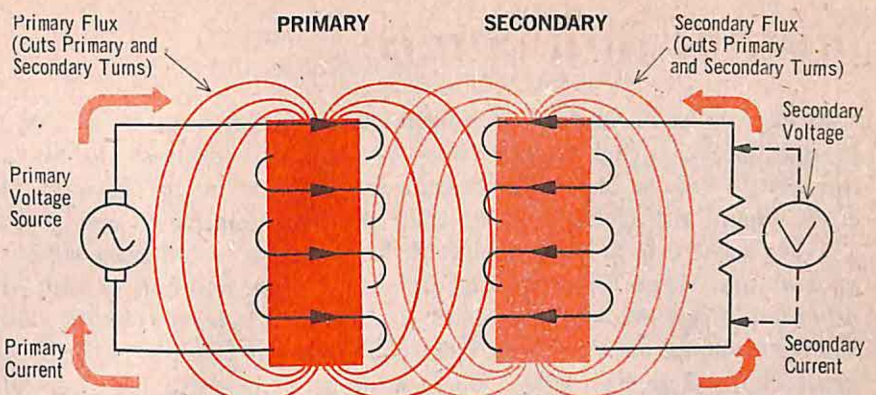
☐ Counter emf voltage can be calculated by: $E_{cemf} = L \times$ number of flux lines, where L is the inductance of the conductor. ☐ Inductance is that property of an electrical circuit that tends to oppose any change in current through the circuit. ☐ Inductance is measured in henrys. Other units are the millihenry, mh; and the microhenry, μh. ☐ Coiled conductors that are inserted into a circuit to deliberately add inductance are called inductors. ☐ Inductors are sometimes called chokes or coils. ☐ A coil is said to be saturated when even large changes in current cannot increase the flux, and very little cemf is produced.

☐ Counter emf can be found by: $\text{cemf} = -L(\Delta I/\Delta t)$. ☐ When an inductor is placed in a d-c circuit, the current will increase in the shape of an exponential waveform. The reverse happens when the circuit is opened. ☐ The time required for the current to increase to 63.2 percent of its maximum value or to decrease to 63.2 percent from its maximum value, is defined as the time constant.

☐ The inductive time constant is equal to: $t = L/R$. ☐ Steady state is reached after five time constants. ☐ Inductance in an a-c circuit has a constant effect on circuit operation: the applied voltage leads the current by 90 degrees, and the cemf lags the current by 90 degrees.

review questions

1. Define *inductive time constant?*
2. How many time constants does it take for the current to reach 63.2 percent of its maximum value in a d-c circuit?
3. In what units are time constants measured?
4. What is the total inductive reactance of three coils in series whose reactances are 5, 5, and 10 ohms?
5. What would be the total inductive reactance for the coils in Question 4 if they were in parallel?
6. What is the inductive reactance of a 10-millihenry coil at frequencies of 100 cps, 1000 cps, 10 kc, 100 kc, and 1 mc?
7. What is the phase relationship between current through, and the voltage across, an inductor? Why is this so?
8. What is the value of the time constant for a circuit consisting of a 5000-ohm resistor and a coil having an inductive reactance of 1.884 ohms at 60 cps?
9. It takes 10 seconds for the current to drop to zero after the switch is opened in a d-c circuit consisting of a battery, switch, resistor, and coil. What is the circuit time constant?
10. If the value for the resistor of Question 9 is 100 ohms, how many 40-henry inductors are needed to provide the inductance? Are they connected in series or in parallel?


Primary Flux (Cuts Primary and Secondary Turns)
PRIMARY
SECONDARY
Secondary Flux (Cuts Primary and Secondary Turns)
Secondary Voltage
Primary Voltage Source
Primary Current
Secondary Current

Varying magnetic field induces voltage in secondary

Mutual induction makes it possible to transfer energy from one circuit to another by means of a changing magnetic field

Magnetic field produced by induced secondary current, itself induces voltage back into primary

mutual induction

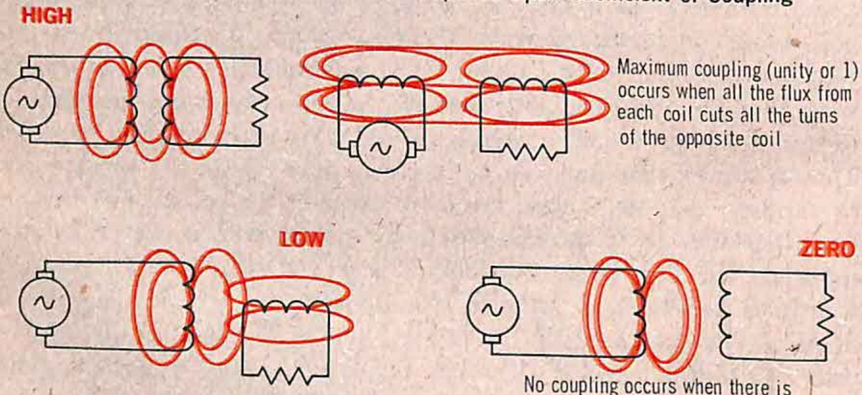
Self-induction in a coil or conductor is actually an induced back emf, which is generated when the magnetic field caused by the current flow cuts the coil or conductor. If the flux lines from the expanding and contracting magnetic field of one coil were to cut the windings of another nearby coil, a voltage would also be induced in that coil. The amount of emf induced in this way depends on the relative *positions* of the two coils. Also, the more turns of the second coil that are cut by the flux lines from the first, the greater will be the emf that is induced. This inducing of an emf in a coil or conductor by magnetic flux lines generated in another coil or conductor is called *mutual induction*. The coil in which the flux originates is called the *primary*, or primary winding, and the one in which the emf is induced is called the *secondary*. Similarly, the current that flows through the primary is the *primary current*, and if the secondary is connected to a load so that current flows, this current is called *secondary current*.

When current flows in the secondary, it sets up its own magnetic field, which induces a voltage back into the primary winding. Thus, when mutual induction occurs between two coils, there are four voltages present. These are (1) the applied voltage in the primary, (2) the self-induced emf in the primary, (3) the induced emf in the secondary, and (4) the emf induced back into the primary by the secondary current. Therefore, the actual or effective overall, inductance of two coils that are mutually coupled is complex because of the complex interactions between the magnetic fields. This effective inductance of two coils that are mutually coupled is called *mutual inductance*.

mutual inductance

Mutual inductance can be considered as the amount or degree of mutual induction that exists between two coils or windings. The mutual inductance of any two coils depends on the *flux linkage* between the coils, which in turn depends on their positions relative to each other. The degree of flux linkage is expressed by a factor called the *coefficient of coupling*. When all of the flux lines from each coil cut, or link, the other coil, the coefficient of coupling is 1, which is the *maximum* value. If only some of the flux lines from each coil cut the other, the coefficient of coupling has some value less than 1. You can see then that when no mutual inductance exists between two coils, the coefficient of coupling between the two is 0. When the value of the coefficient of coupling is close to 1, the two coils are said to have tight coupling; and when the value is much less than 1, the coils have loose coupling. The term *critical coupling* is used to describe the dividing line between loose and tight coupling.

Mutual Inductance Between Coils Depends Upon Coefficient of Coupling



Maximum coupling (unity or 1) occurs when all the flux from each coil cuts all the turns of the opposite coil

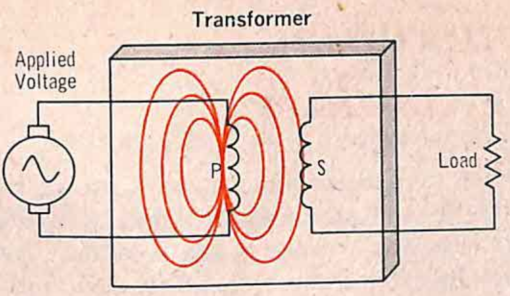
Minimum coupling occurs when two coils are at right angles

No coupling occurs when there is no mutual inductance between the coils

When the coefficient of coupling between two coils is known, the total inductance of the coils is found by multiplying the values of inductance of the coils, taking the square root of the result, and multiplying it by the coefficient of coupling. As an equation, this is given by:

$$M = k\sqrt{L_1 \times L_2}$$

where M is the total inductance of the mutually coupled coils, in henrys; k is the coefficient of coupling; and L_1 and L_2 are the individual inductances of the coils, in henrys.



In a transformer, electrical energy is transformed from the primary circuit to the secondary circuit by means of a the mutual inductance between the transformer windings. The sequence of this energy transfer is

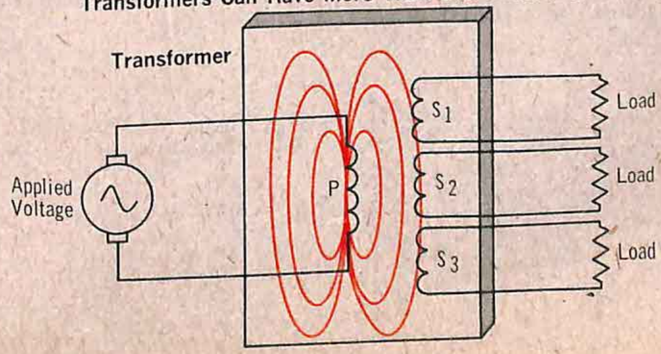
APPLIED VOLTAGE → PRIMARY CURRENT → MAGNETIC FIELD → INDUCED SECONDARY EMF → SECONDARY CURRENT → ENERGY TO LOAD

the transformer

When mutual induction exists between two coils or windings, a change in current through one induces a voltage in the other. Devices which make use of this principle are called *transformers*. Every transformer has a primary winding and one or more secondary windings. The primary winding receives electrical energy from a power source and couples this energy to the secondary winding by means of a changing magnetic field. The energy appears as an emf across the secondary winding, and if a load is connected to the secondary, the energy is transferred to the load.

By means of transformers, electrical energy can be transferred from one circuit to another, with no physical connection between the two. The energy transfer is accomplished completely by the magnetic field. The transformer thus acts as a coupling device. Transformers are also indispensable in a-c power distribution, since they can convert electrical power at a given current and voltage into the equivalent power at some other current and voltage.

Transformers Can Have More Than One Secondary Winding

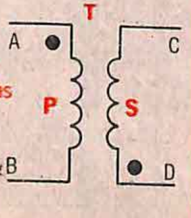


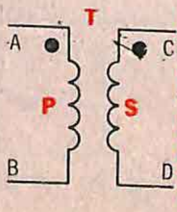
transformer operation with open secondary

You will remember that when mutual induction exists between two coils, not only does the current in the primary coil induce a voltage in the secondary coil, but the resulting current in the secondary coil, in turn, induces a voltage *back* into the primary coil. This occurs in a transformer, and it is in large part responsible for how a transformer works. However, for ease of understanding, transformer operation will first be described for the case of a transformer having an *open secondary*. No current flows in the secondary in this case, and so no voltage is induced back into the primary. After the description of how a transformer with an open secondary works, a complete transformer, with current flowing in both the primary and the secondary, will be described.

In a transformer having an open secondary, the primary operates essentially the same as an inductor. This means that the primary current *lags* the applied voltage by 90 degrees and at the same time *leads* the back emf by 90 degrees. The applied voltage and the back emf are thus of *opposite* polarity. Most transformers are designed to have large back emf's in the primary when the secondary is open, so the primary current is therefore *very low*. As the magnetic field around the primary winding, caused by the changing current through the primary, alternately expands and collapses, it cuts the turns of the secondary winding, thereby inducing a voltage in the secondary. The voltage induced in the secondary is *maximum* when the rate of *change* of the primary current is *greatest* (0, 180, and 360 degrees), and *zero* when the primary current is *not changing* (90 and 270 degrees). When this relationship is plotted, as on page 3-75, you can see that the secondary voltage lags the primary current by 90 degrees. Since the primary applied voltage leads the primary current, the secondary voltage is therefore 180 degrees out of phase with the primary voltage. It is also in phase with the back emf in the primary.

Usually, the letter T designates a transformer, with P as the primary, and S as the secondary, or secondaries





Sometimes, dots are used to indicate the in-phase terminal of the two windings. The schematic symbols alone do not show phase relationships because external wires can be crossed to make the output in phase with the input

voltage and current

PHASE RELATIONSHIPS IN TRANSFORMER WITH UNLOADED SECONDARY

Voltage Applied to Primary

- Lead primary current by 90°
- 180° out of phase with back emf
- 180° out of phase with secondary voltage

Primary Current

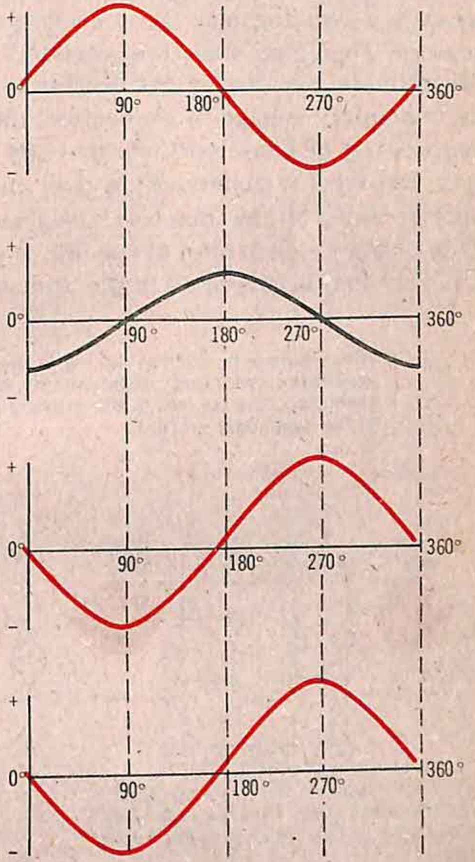
- Lags applied voltage by 90°
- Leads back emf by 90°
- Leads secondary voltage by 90°

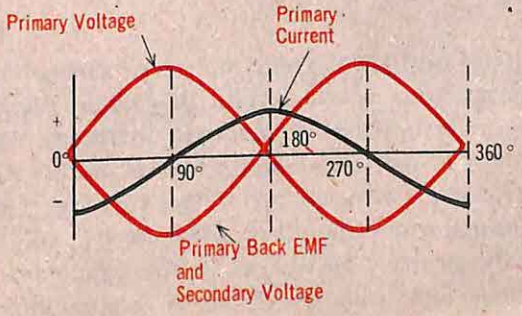
Back EMF Induced in Primary

- Lags primary current by 90°
- 180° out of phase with applied voltage
- In phase with secondary voltage

Secondary Voltage

- Lags primary current by 90°
- 180° out of phase with applied voltage
- In phase with back emf

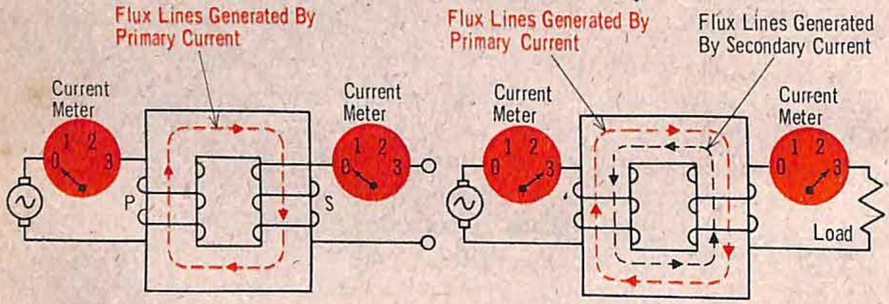




transformer operation with loaded secondary

When a *load* is connected to the secondary of a transformer, current flows in the secondary. As in any inductance, the *current* through the secondary winding *lags* the secondary *voltage* that produces it by 90 degrees. Therefore, since the secondary voltage, as you remember, lags the primary current by 90 degrees, and the secondary current lags the secondary voltage by 90 degrees, then the secondary current is 180 degrees out of phase with the primary current. As the secondary current changes, it generates its own magnetic field, whose flux lines *oppose* those of the magnetic field created by the primary current. This *reduces* the strength of the primary magnetic field, and as a result, *less back emf* is generated in the primary. With less back emf to oppose the applied voltage, the primary current *increases*. The amount of increase is in *direct proportion* to the current flowing in the secondary. Thus, when secondary current in a transformer increases, the primary current automatically also increases. And when secondary current decreases, the primary current does likewise. You can see, then, that if the secondary of a transformer should become *shorted*, too much current would flow in the primary as well as in the secondary. Not only would the transformer burn out, but there is a possibility that the source supplying power to the primary would also be damaged.

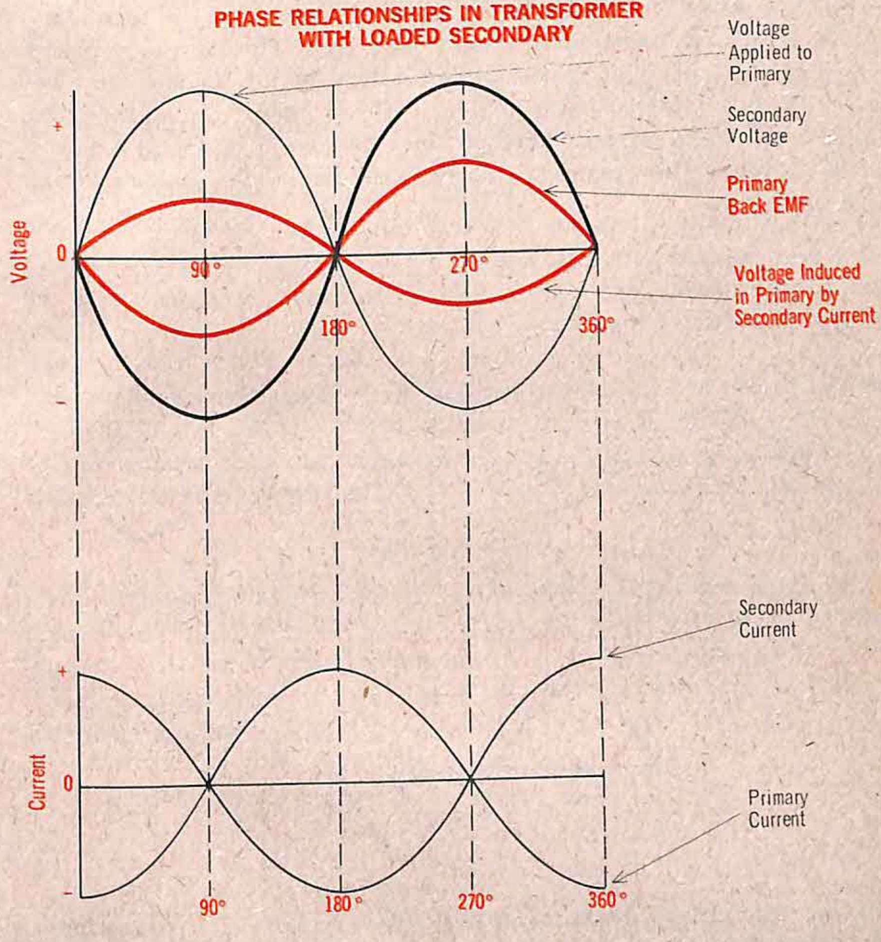
When there is no current flowing in the secondary of a transformer, very little current flows in the primary. But, when current flows in the secondary, the current in the primary goes up in direct proportion to the secondary current


Flux Lines Generated By Primary Current
Current Meter
0 1 2 3
P
S
Current Meter
0 1 2 3
Flux Lines Generated By Primary Current
Flux Lines Generated By Secondary Current
Current Meter
0 1 2 3
Current Meter
0 1 2 3
Load

With an open secondary, only flux lines caused by primary current exist. The primary current is limited by the back emf, which is normally quite large

Secondary current produces flux lines that oppose those caused by primary current. This causes a decrease in back emf, and a resulting increase in primary current

voltage and current



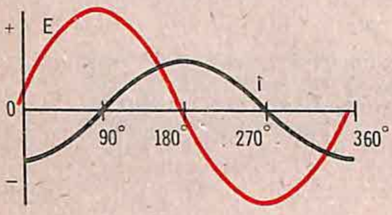
PHASE RELATIONSHIPS IN TRANSFORMER WITH LOADED SECONDARY

The secondary current is 180° out of phase with the primary current. The secondary current induces a voltage in the primary that opposes the back emf of the primary. This causes the back emf of the primary to decrease, and allows more primary current to flow

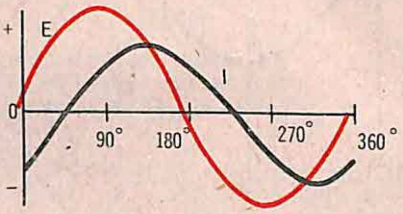
effect of load on phases

The 90-degree phase difference (between the voltage and current in both the primary and the secondary) actually only exists when the secondary current is very small. When the resistance of the secondary load is decreased, secondary current increases. This is often called *increasing the load.* This makes the secondary circuit become more resistive. With a more resistive load, the phase difference between the voltage and current becomes smaller, since they are in phase in a purely resistive circuit. The greater the secondary current, the smaller is the phase angle.

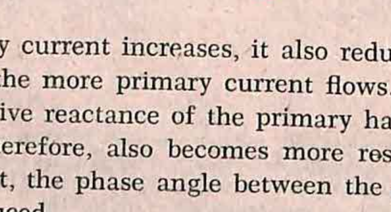
No-Load Current



Medium-Load Current



Heavy-Load Current



As the secondary current increases, it also reduces the back emf in the primary, and the more primary current flows. Since the cemf decreases, the inductive reactance of the primary has been reduced. The primary circuit, therefore, also becomes more resistive as current increases. As a result, the phase angle between the primary voltage and current is also reduced.

In summary, then, when very little current flows in the secondary of a transformer that contains a resistive load, the voltage and current in both the primary and secondary are 90 degrees out of phase. But as the secondary load increases, the phase angle between primary voltage and current, and secondary voltage and current becomes smaller (closer to 0 degrees). This is more fully explained in Volume 4.

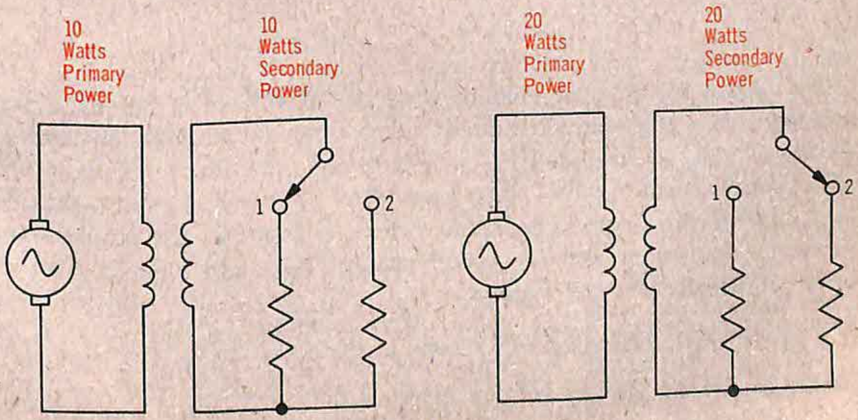
primary and secondary power

A transformer actually transfers electric *power* from the primary to the secondary circuit. The primary circuit *draws* the power from the *source*, and the secondary *delivers* the power to the *load*. The power transferred from the primary to the secondary is determined by the current flowing in the secondary, which, in turn, depends on the power required by the load. If the load requires a great deal of power, such as would be the case for a low-resistance load, a high current will flow in the secondary. As you learned previously, this high current will cause a decrease in the back emf of the primary, and the primary current will increase; this will produce the stronger magnetic field necessary for the high secondary current. The transformer thus regulates the power transferred from the source to the load in response to the load requirements.

In an *ideal* transformer, the power in the primary circuit equals the power in the secondary circuit. Since power equals current times voltage, the equation for the relationship between the primary power (P_p) and the secondary power (P_s) in an ideal transformer is

$$E_p \times I_p = E_s \times I_s$$

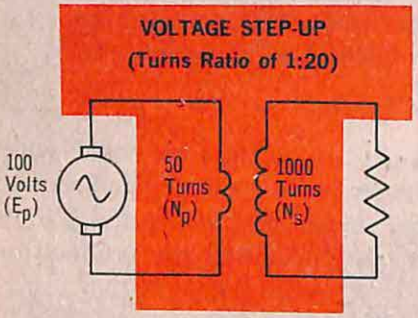
Thus, assuming that primary and secondary voltages are equal, which is the case when the transformer primary and secondary windings have the *same* number of *turns*, the primary current will automatically adjust to the same value as the secondary current so that the primary and secondary powers are equal.



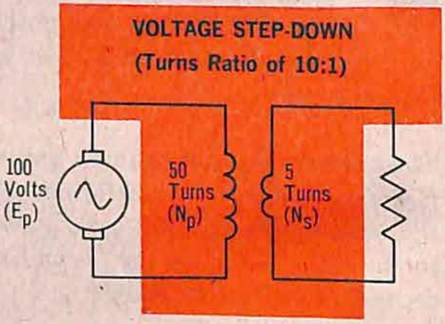
In an ideal transformer, the power in the primary circuit equals the power in the secondary circuit

turns ratio vs. voltage and current

As was mentioned, an important use of the transformer in power transmission is to convert power at some values of current and voltage into the *same power* at some *other values* of current and voltage. Basically, this can be done because with a given applied voltage in the primary, the secondary voltage depends on the number of *turns* in the *secondary* winding as compared to the number of *turns* in the *primary* winding. When the secondary winding has *more* turns than the primary, the secondary voltage is *greater* than the primary voltage. A step up in voltage, therefore, takes place, and the transformer is called a *step-up transformer*. Likewise, if the secondary winding has *fewer* turns than the primary, the secondary voltage is lower than the primary voltage, and the transformer is called a *step-down transformer*.



$E_s = E_p\,(N_s/N_p) = 100 \times (1000/50) = 2000$ volts



$E_s = E_p\,(N_s/N_p) = 100 \times (5/50) = 10$ volts

The reason for this increase or decrease in voltage is simple if you remember that the voltage induced in any coil is actually the sum of the many voltages induced in each loop that the flux lines cut. The more loops, therefore, the more individual voltages are induced, and the greater is their sum. The exact relationship in an ideal transformer between the primary and secondary voltages (E) and their number of turns (N) is given by the equation:

$$E_p/N_p = E_s/N_s \qquad \text{or} \qquad E_p/E_s = N_p/N_s$$

Therefore, the secondary voltage is equal to:

$$E_s = E_p\left(\frac{N_s}{N_p}\right)$$

turns ratio vs. voltage and current (cont.)

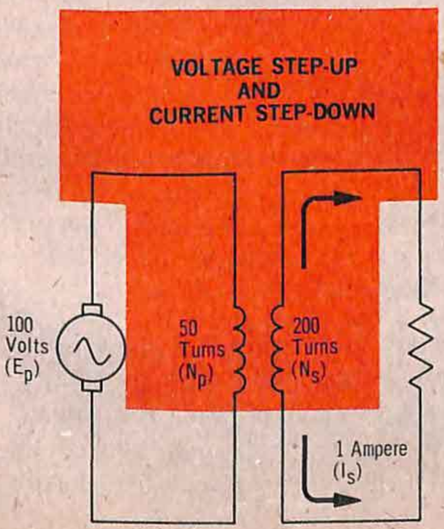
The relative number of turns in the windings (N_p/N_s) is called the *turns ratio* of the transformer, and is usually expressed as a proportion; for example, 10:1, 50:1, 1:20, etc. You can see from the equation that if the secondary has *twice the turns* as the primary (turns ratio of 1:2), the secondary voltage is *twice* the *primary voltage*. Similarly, if the secondary only has *half the turns* of the primary (turns ratio of 2:1), the secondary voltage is *half* the *primary voltage*.

Since the turns ratio determines the relationship between primary and secondary voltages, and since ideally, the power in the primary is equal to the power in the secondary, then there must also be a relationship between the turns ratio and the primary and secondary *currents*. From the power equation ($P = EI$), you can see that for the primary and secondary powers to be equal, the winding with the *higher voltage*, and therefore more turns, must have a *lower current* in it. Similarly, the winding with the *lower voltage*, and therefore fewer turns, must have a *higher current*. This relationship between the turns ratio and the primary and secondary currents is expressed by the equation:

$$I_p \times N_p = I_s \times N_s \qquad \text{or} \qquad I_s/I_p = N_p/N_s$$

Therefore, the primary current is equal to:

$$I_p = I_s \left(\frac{N_s}{N_p}\right)$$



VOLTAGE STEP-UP AND CURRENT STEP-DOWN

$$I_p = I_s\,(N_s/N_p) = 1 \times (200/50) = 4 \text{ amperes}$$

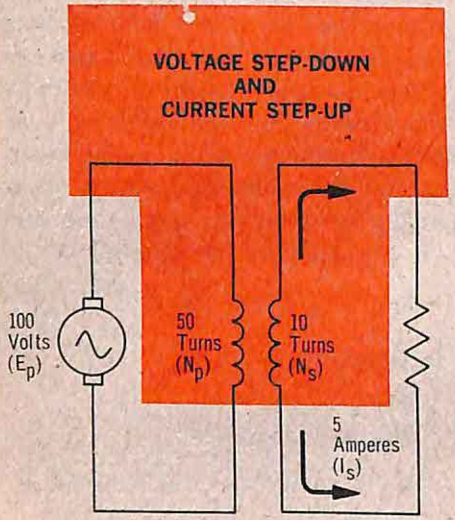
$$E_s = E_p\,(N_s/N_p) = 100 \times (200/50) = 400 \text{ volts}$$

$$P_p = E_p \times I_p = 100 \times 4 = 400 \text{ watts}$$

$$P_s = E_s \times I_s = 400 \times 1 = 400 \text{ watts}$$

turns ratio vs. voltage and current (cont.)

The equation expressing the relationship between the turns ratio and the primary and secondary currents tells us that the current in the primary times the number of turns in the primary winding is equal to the current in the secondary times the number of turns in the secondary winding. The current times the number of turns is often called the *ampere-turns*. And so, the ampere-turns of the primary equals the ampere-turns of the secondary.



$I_p = I_s\,(N_s/N_p) = 5 \times (10/50) = 1$ ampere

$E_s = E_p\,(N_s/N_p) = 100 \times (10/50) = 20$ volts

$P_p = E_p \times I_p = 100 \times 1 = 100$ watts

$P_s = E_s \times I_s = 20 \times 5 = 100$ watts

If you compare the relationships of the turns ratio with voltages and currents, that is

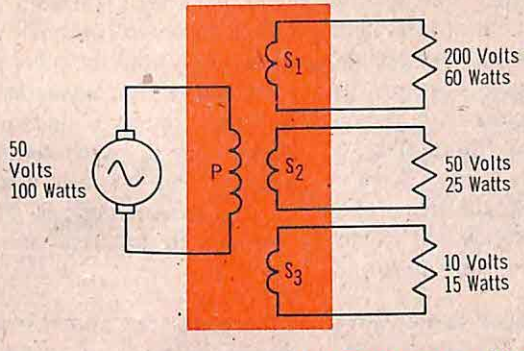
$$E_p/E_s = N_p/N_s$$

and

$$I_s/I_p = N_p/N_s$$

you can see that the primary-secondary current ratio is the *opposite* of the primary-secondary voltage ratio. A transformer with a 1:50 step-up in voltage, therefore, has a 50:1 step-down in current. You can see, then, that power at one current and voltage can be converted to the same power at any other current and voltage by a transformer having the appropriate turns ratio.

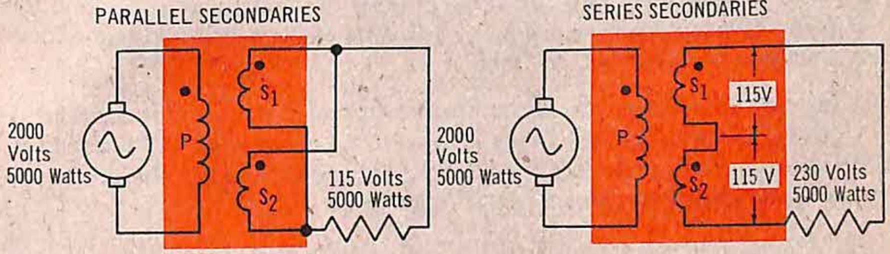
Independent Multiple Secondary Windings



In transformers with multiple secondary windings, the power in the primary is equal to the sum of the powers in the individual secondaries:

$$P_P = P_{S_1} + P_{S_2} + P_{S_3} + \ldots + \text{etc.}$$

Multiple Secondary Windings Connected to Common Load



multiple-secondary transformers

There is a type of transformer that has a *single* primary winding but *more than one* secondary winding. All of the secondary windings may be step-up or step-down windings, or some may be step-up and some step-down. The voltage induced in each secondary winding is *independent of* the other windings, and is determined, as in any simple transformer, by the primary voltage and the ratio of the number of turns of the secondary to those of the primary winding.

In some applications, the secondary windings are connected to individual, independent circuits. In the transmission of electric power, though, it is common to use transformers having two secondaries, and to connect the secondary windings either in series or parallel. Both secondaries then deliver power to the same load. When the windings are connected in series, if their polarities are in the same direction, their voltages add; they conduct the same current. If their polarities are opposing, their voltages will subtract. Secondary windings are usually connected in parallel so that greater current can be supplied to a load with less loss.

summary

☐ Mutual induction exists between two coils when the flux lines generated in one coil cut the turns of the other. ☐ Mutual induction between two coils is given by: $M = k\sqrt{L_1L_2}$. ☐ Transformers make use of the mutual inductance between two coils, or windings. ☐ With an open secondary, the secondary transformer voltage is 180 degrees out of phase with the primary voltage. It is in phase with the back emf of the primary. ☐ When a load is connected to the secondary of a transformer, current flows in the secondary. The secondary current, in turn, creates a magnetic field, which induces an emf back in the primary. ☐ Shorting the secondary can cause the primary to draw excessive current, which may damage the transformer.

☐ The value of the secondary load has an effect on the phase angles between primary voltage and current, and secondary voltage and current. ☐ In an ideal transformer, the power in the primary equals the power in the secondary. ☐ The ratio of the number of turns in the primary to the number of turns in the secondary is called the turns ratio. ☐ The ratio of the primary to the secondary voltage is equal to the turns ratio.

☐ The ratio of the secondary to the primary current is equal to the turns ratio. ☐ The ampere-turns of the primary is equal to the ampere-turns of the secondary. ☐ In multiple-secondary transformers, the total power in the primary is equal to the sum of the powers of the secondaries.

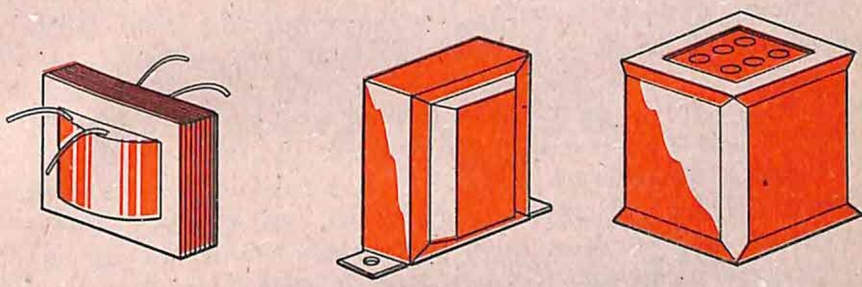
review questions

1. What is *mutual induction*? What are its units?
2. What is meant by *coupling coefficient*?
3. What is the mutual inductance of two coils, each having an inductance of 14 millihenrys, when the coefficient of coupling is 0? 1/4? 1/2? 3/4? 1?
4. What is a *transformer*?
5. What is the *turns ratio* of a transformer?
6. What is the phase relationship between the primary and secondary voltages of a transformer with an open-circuited secondary?
7. In an ideal transformer, what is the relationship between the power in the primary and the power developed by the secondary?
8. The primary voltage of a transformer with a turns ratio of 1:9 is 120 volts. What is the voltage across the secondary?
9. A transformer whose primary draws 2000 watts has five equal secondaries. How much power is developed by each secondary?
10. What is meant by *ampere-turns*?

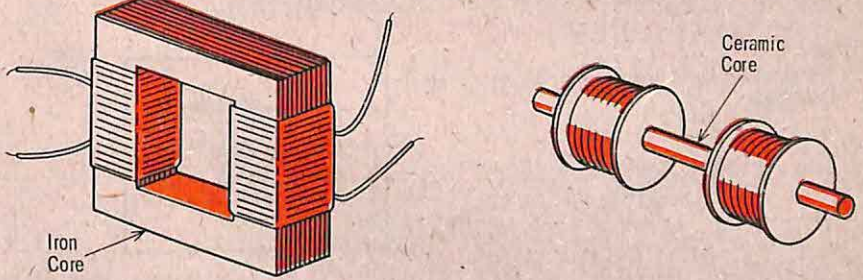
types of transformers

There are many types of transformers in use today. Each type is designed, and therefore best suited, for a particular use. They vary not only in physical characteristics, such as size and shape, but in electrical characteristics and efficiency as well. A complete description of all the various types of transformers used is beyond the scope of this volume. However, there are certain basic categories into which all transformers fall. These categories will be described on the following pages.

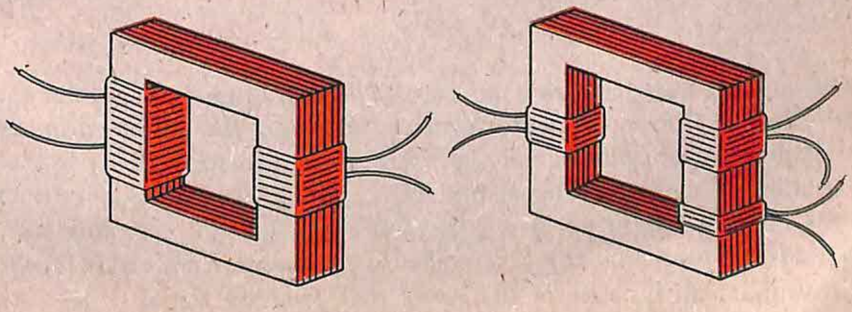
TRANSFORMERS VARY IN SIZE AND SHAPE



TRANSFORMERS VARY IN CORE MATERIAL

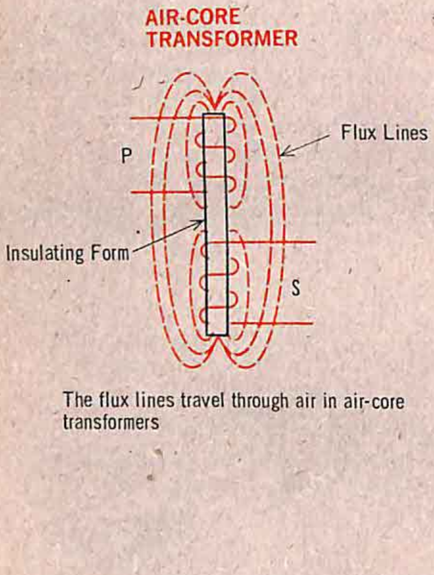


TRANSFORMERS VARY IN TURNS RATIO

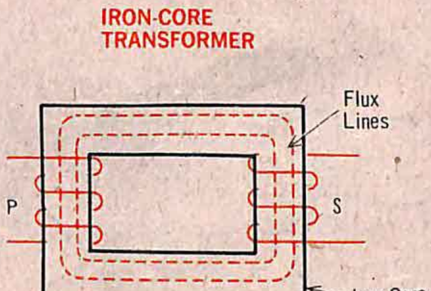


iron-core and air-core transformers

The two broadest categories of transformers are *iron-* and *air-core transformers*. They obtain their names from the materials between the primary and secondary windings through which the flux lines travel. The windings of air-core transformers are around *insulating* forms, and the flux lines follow a path in *air* between the windings. Air does not offer as good a path for the flux lines as does iron, and so the coupling between the primary and secondary windings is less than that obtained if an iron core was used. The maximum coefficient of coupling possible with air-core transformers is about 0.65, which is much less than that provided by iron-core transformers. As a result, the simple primary–secondary power ratios do not apply to air-core transformers, since these formulas are based on almost perfect coupling. This is explained more fully for transformer efficiency, covered later. Generally, air-core transformers are used only at high frequencies, where iron-core transformers are impractical because of the losses that occur in them.



The flux lines travel through air in air-core transformers

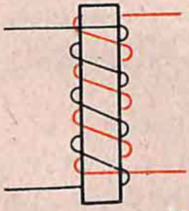


The flux lines travel through soft or powdered iron in iron-core transformers

iron-core and air-core transformers (cont.)

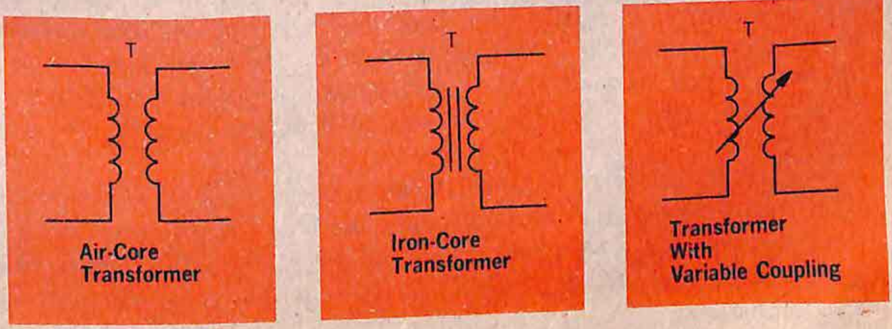
Iron-core transformers usually have a core made of soft or powdered iron. The windings are wound around the iron core, and the flux lines travel through the core between the windings. The flux lines cause the core itself to become magnetized in the same direction, and this results in a large increase in the total number of flux lines. A high degree of coupling is possible with such cores. To further improve the coupling, the primary and secondary windings are sometimes wound *on top* of each other. Coefficients of coupling as high as 0.98 can be obtained in transformers having iron cores. These high coefficients result in iron-core transformers having characteristics close to those of an ideal transformer. These are the transformers that are used for the transmission of power.

There is a type of radio transformer in which the coupling can be varied. This is done by changing the positions of the primary and secondary windings relative to each other. As explained earlier, when the windings are at right angles to one another, there is zero coupling. When they are parallel, there is maximum coupling (1.00). In any in-between angle, any degree of coupling can be obtained. Another method of changing the coupling is to pass a magnetic shield between the windings of an air-core transformer.



A method of increasing transformer coupling is to interwind the primary and secondary around the core

TRANSFORMER SYMBOLS



Air-Core Transformer

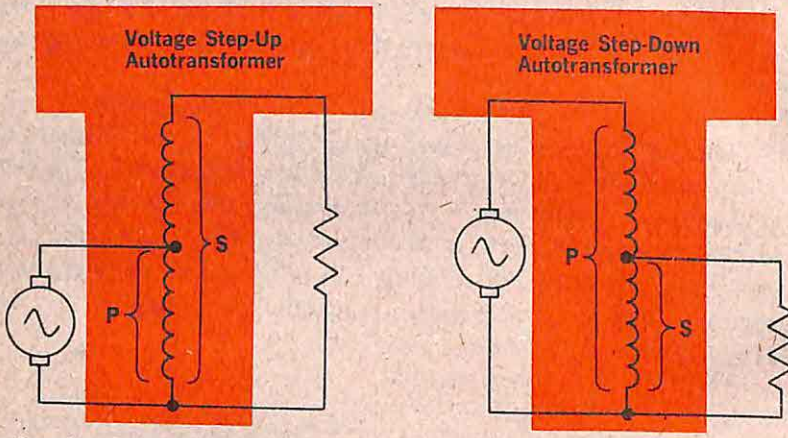
Iron-Core Transformer

Transformer With Variable Coupling

the autotransformer

There is a special type of iron-core transformer which physically has only *one* winding. Functionally, though, the one winding serves as *both* the primary and secondary. This type of transformer is called an *autotransformer*. When an autotransformer is used to step up the voltage, part of the single winding acts as the primary, and the entire winding acts as the secondary. When an autotransformer is used to step down the voltage, the entire winding acts as the primary, and part of the winding acts as the secondary.

The single winding of an autotransformer serves as both the primary and the secondary


Voltage Step-Up Autotransformer
S
P
Voltage Step-Down Autotransformer
P
S

When the voltage is stepped up, part of the winding is the primary, and the entire winding is the secondary

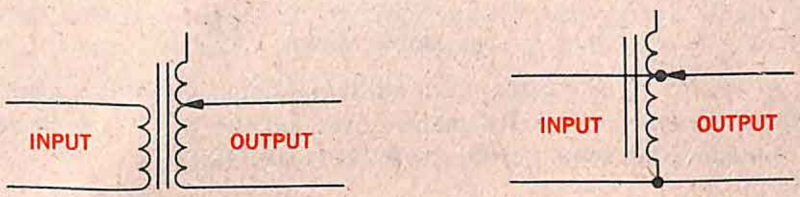
When the voltage is stepped down, the entire winding acts as the primary, and part of the winding acts as the secondary

The action of an autotransformer is basically the same as the standard two-winding transformer. Power is transferred from the primary to the secondary by the changing magnetic field, and the secondary in turn regulates the current in the primary to set up the required condition of equal primary and secondary power. The amount of step-up or step-down in voltage depends on the turns ratio between the primary and secondary, with each winding considered as separate, even though some turns are *common* to both the primary and secondary.

A disadvantage of the autotransformer is the lack of *isolation* between the primary and secondary circuits. This results from the primary and secondary both using some of the same turns. Despite this disadvantage, the autotransformer is used in many circuits because it is inexpensive.

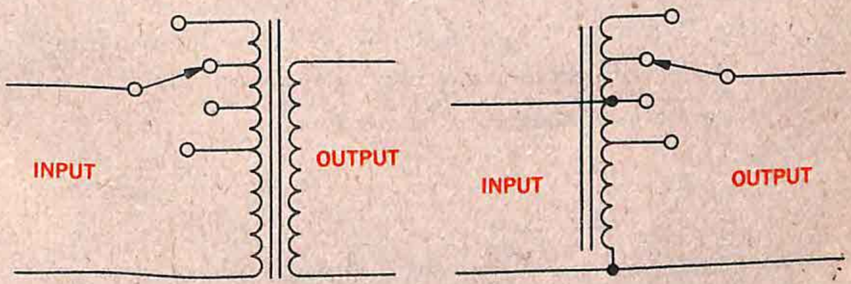
the adjustable transformer

Transformers can be made similar to variable resistors, so that their output voltages can be set to a specific value. Such transformers are used in power line regulators, where it is important to get an exact line voltage. Such a transformer generally uses a sliding contact that can be positioned to obtain just the right turns ratio for the proper output voltage when the value of the input voltage may not be reliable. This can be done with a regular transformer, or with an autotransformer.



The output voltage of either of these transformers can be adjusted from 0 to some maximum value

Another method to obtain the proper output voltage uses a special transformer with a tapped winding. Either the primary or secondary can be tapped, and a switch picks out the turns ratio. But this method does not allow as precise control as does the transformer with the sliding contact. However, transformers can be made using both these methods. For example, a switch with a tapped primary for a *coarse* adjustment, and a sliding contact on the secondary for a *fine*, or *vernier*, adjustment.



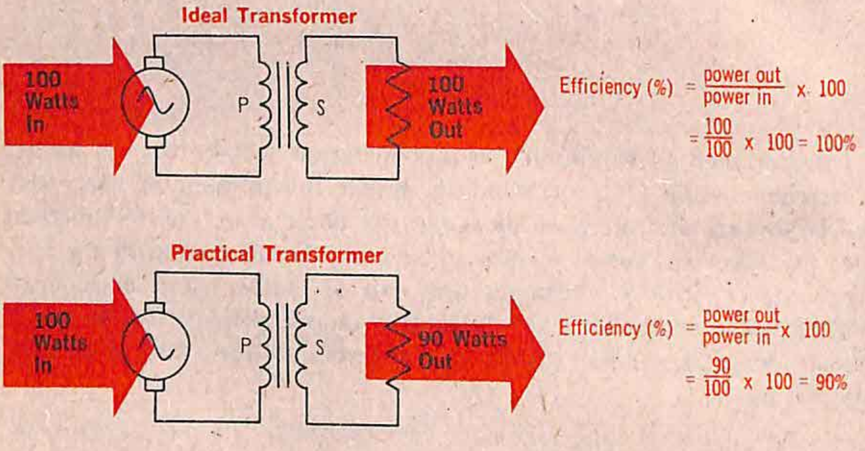
The output voltage of either of these transformers can be adjusted within a range to get close to the desired value

transformer losses

You remember that in an ideal transformer the power in the secondary is exactly *equal* to the primary power. This is true for a transformer with a coefficient of coupling of 1.0 (complete coupling) and no internal losses. In practice, such a transformer cannot be made. The degree to which any transformer approaches these ideal conditions is called the *efficiency* of the transformer. Mathematically, the efficiency is equal to the output (secondary) power divided by the input (primary) power. Or,

$$\text{Efficiency (\%)} = \frac{\text{output power}}{\text{input power}} \times 100$$

You can see from this equation that when the output and input power are equal, the efficiency is 100 percent. The smaller the output power is in relation to the input power, the lower is the efficiency.



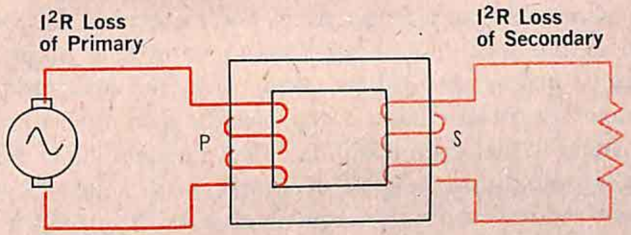
In any practical transformer, the output power is less than the input power and so the efficiency is less than 100%. The lost, or wasted, power is the result of transformer losses, and less than complete coupling

Since transformer losses reduce the efficiency of a transformer, and therefore represent wasted power, these losses are usually kept to a minimum. This is especially true in the design of iron-core transformers that must deliver large amounts of power. The most common type of transformer losses are described on the following pages.

copper loss and leakage

Transformer windings are usually made of many turns of copper wire. As with any wire, these windings have *resistance*. The *more turns* there are to the windings, the longer is the effective length of the wire, and so the *greater* is the *resistance*. When the primary and secondary currents flow through the windings, power is *dissipated* in the form of heat. These I^2R losses are called *copper losses*, and are proportional to the square of the current and to the resistance. Copper losses can be minimized by winding the transformer primary and secondary with wire that has a large cross-sectional area, but this increases the size and weight of the transformer.

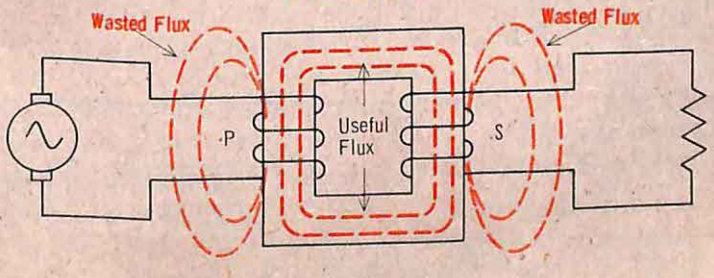
COPPER LOSSES



Copper losses result from the resistance of the wire used for the transformer windings

A source of inefficiency in iron-core transformers results from the fact that not all of the flux lines produced by the primary and secondary windings travel through the iron core. Some of the lines *leak* from the windings out into space, and therefore do not link the primary and secondary. This leakage of the flux lines represents *wasted* energy.

FLUX LEAKAGE

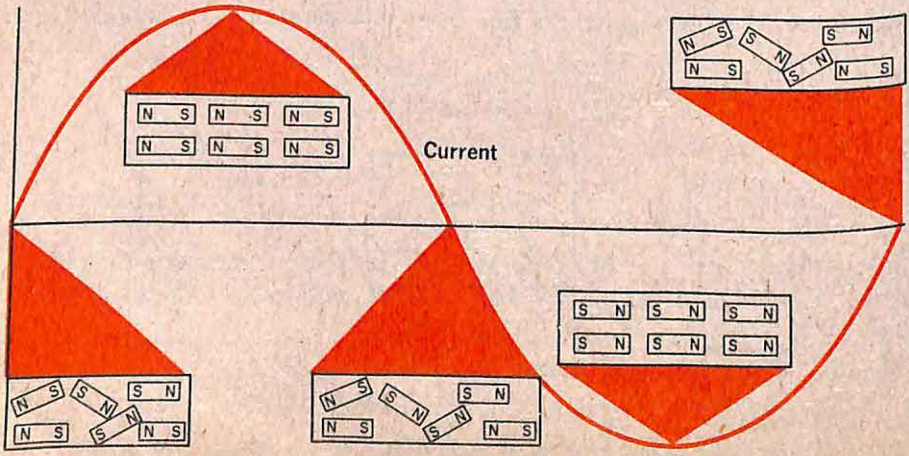


Leakage is caused by the fact that not all of the flux lines travel through the iron core

hysteresis loss

In an iron-core transformer, the core is magnetized by the magnetic field created by the current through the windings. The direction in which the core is magnetized is the same as the direction of the magnetic field that causes it to become magnetized. Thus, each time the magnetic field around the windings expands and collapses, the direction in which the core is magnetized also changes. You will remember from Volume 1 that each molecule of iron behaves as a small individual magnet. To magnetize a piece of iron, all or most of these individual magnets must be aligned in the *same* direction. Therefore, every time the direction of magnetization of the core reverses, the molecules of the core turn around to become aligned in the new direction of the flux lines. However, the molecules do not follow the reversals of the magnetic field exactly.

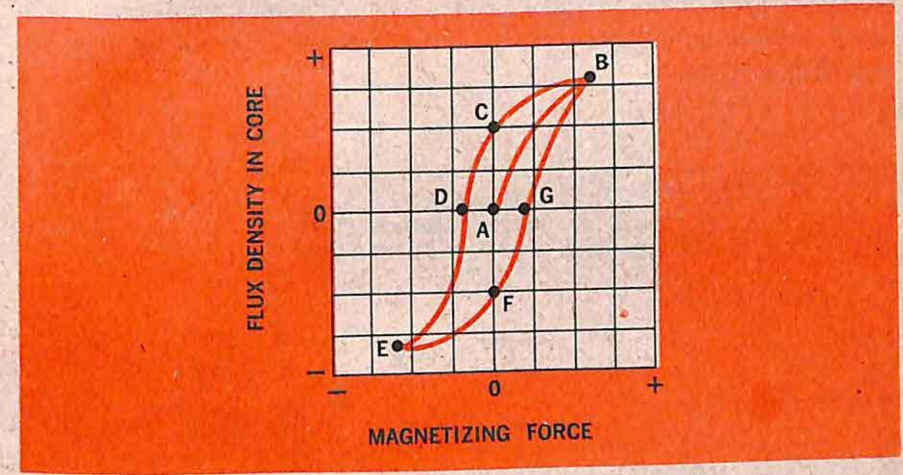
When the core is initially magnetized, the molecules are aligned in the direction of the field. But when the magnetic field drops to zero, the molecules do not return to their original random orientations. As a result, although the magnetizing force has dropped to zero, the core still retains some of its magnetization. The magnetic field has to reverse direction and apply a magnetizing force in the opposite direction before the core returns to its unmagnetized state. The molecules then reverse and orient themselves in the new direction of the field. The lagging behind the magnetizing force by the molecules is called *hysteresis*. The energy that has to be supplied to the molecules to cause them to turn around and, in effect, try to catch up with the magnetic field, is called the *hysteresis loss* of the core. The more energy that is required, the greater is the hysteresis loss.



hysteresis loop

Hysteresis losses depend mainly on the type of core material used. Materials that retain a large part of their magnetization after the magnetizing force is removed have high hysteresis losses. These materials are said to have a high *permanence*.

For a given core material, hysteresis losses are directly proportional to the frequency of the current in the transformer. The higher the frequency, the more times per second the molecules of the core material must reverse their alignment; and so the larger is the total energy required for this purpose. This relationship between hysteresis loss and frequency is one of the main reasons why iron-core transformers cannot be used in applications involving high frequencies.



A hysteresis loop is a curve that shows how the magnetization of a material lags behind the magnetizing force. It can, therefore, be used to indicate hysteresis loss. On the curve shown, point A corresponds to no magnetizing force, and therefore no core flux.

When the magnetizing force is first applied in the positive direction, the curve travels to point B, which corresponds to core flux in the positive direction. When the magnetizing force drops to zero (point C), you can see that there is still flux in the core in the positive direction. The magnetizing force has to reverse direction and reach point D before the material is demagnetized (zero flux density).

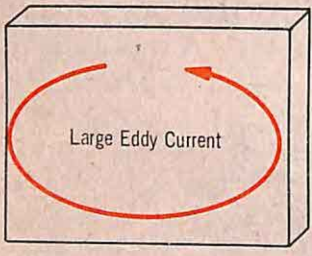
You can follow the remainder of the first cycle of the magnetizing force (D to E), and the complete second cycle (EFGBCDE), and see how the magnetization of the core lags behind the magnetizing force.

eddy current loss

Since the iron core of a transformer is a *conducting* material, the magnetic field of the transformer *induces* a voltage in the *core*. This voltage then causes small *currents* to flow within the core. These currents are called *eddy currents*. Eddy currents can be considered as short-circuit currents, inasmuch as the only resistance they encounter is the small resistance of the core material. Like hysteresis losses, eddy currents remove energy from the transformer windings, and so represent wasted power.

Eddy currents in a transformer core are reduced by dividing the core into many flat sections, or *laminations*, with the laminations insulated from each other by means of an insulating coating applied to both sides of the lamination. The eddy currents can then only flow in the individual laminations. And since the laminations have very small cross-sectional areas, the resistance offered to the eddy currents is greatly increased.

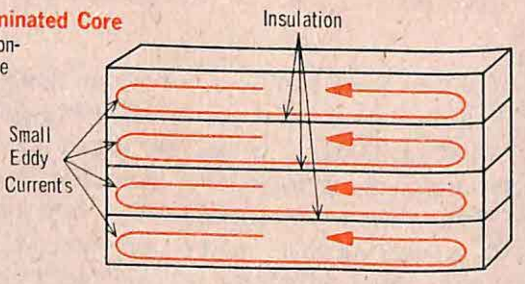
Unlaminated Core



In an unlaminated core, the eddy currents are limited only by the small resistance of the core material. The currents are, therefore, large

Laminated Core

In a laminated core, the eddy currents are confined to the small cross-sectional area of the individual laminations. This increases the resistance to the eddy currents, thereby keeping them small



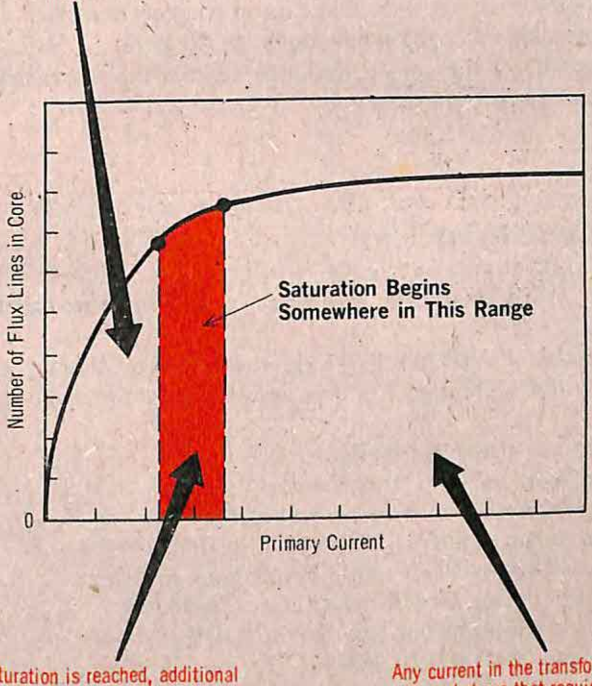
The power loss due to eddy currents is proportional to both the *frequency* and *magnitude* of the current in the transformer. Eddy current losses, like hysteresis losses, therefore limit the use of iron-core transformers in applications involving high frequencies.

saturation loss

When the current in the primary of an iron-core transformer increases, the flux lines generated follow a path through the core to the secondary winding, and back through the core to the primary winding, As the current first begins to increase, the number of flux lines in the core increases *rapidly*. The more the current rises, the greater is the number of flux lines existing in the core. When the current has risen to the point where there are a *great number* of flux lines in the core *(high flux density)*, additional increases in current produce only a *few* additional flux lines. The core is then said to be *saturated*. Any further increases in primary current after core saturation has been reached results in wasted power, since the magnetic field cannot couple the additional power to the secondary.

CORE SATURATION

Before saturation is reached, small changes in current result in relatively large increases in the number of flux lines in the core



When saturation is reached, additional increases in current have little effect on the number of flux lines in the core

Any current in the transformer primary over and above that required to produce saturation results in wasted power

summary

☐ Air-core transformers are wound around insulating forms, and the flux lines pass through the air between the windings. ☐ The maximum coefficient of coupling possible for air-core transformers is 0.65. ☐ Iron-core transformers have as their core iron, which provides a better path for the flux lines. ☐ The autotransformer has only one winding, which is tapped. ☐ A disadvantage of the autotransformer is the lack of isolation between the primary and secondary circuits.

☐ Variable transformers have sliding contacts or different taps. This permits the transformer to have various voltages, depending on where the slide is set or which tap is used. ☐ The efficiency of a transformer indicates the ratio of the output power to the input power. ☐ The difference between the transformer's input power and output power is due to the transformer losses. ☐ Transformer losses include: copper loss, leakage, hysteresis loss, eddy current loss, and saturation loss.

☐ Copper loss is due to the heat dissipated in the windings by current flow. These are sometimes called I^2R losses. ☐ Leakage is due to some lines of flux not linking both primary and secondary. This leakage represents wasted energy. ☐ Hysteresis loss depends on the type of core material used. It is directly proportional to frequency. ☐ Eddy current loss is due to circulating currents or short-circuit currents that flow in the core material. These losses are reduced by using insulated laminations for the core. ☐ Saturation loss is due to the inability of the core material to contain the increased number of flux lines when high current flows.

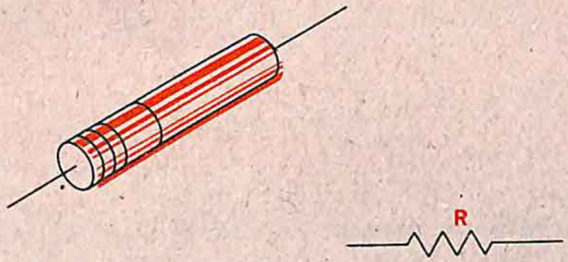
review questions

1. How many separate windings does an autotransformer have?
2. Does the autotransformer have isolation between the primary and secondary? Is this an advantage or disadvantage? Why?
3. When are iron-core transformers used?
4. What is an *air-core transformer*?
5. What is meant by *transformer efficiency*?
6. What is the efficiency of an ideal transformer?
7. What is a *hysteresis loop*? What does it indicate?
8. What is meant by *I^2R losses* in a transformer?
9. What is the difference between *hysteresis loss* and *eddy current loss* in a transformer?
10. What is meant by a *saturated core*?

RL circuits

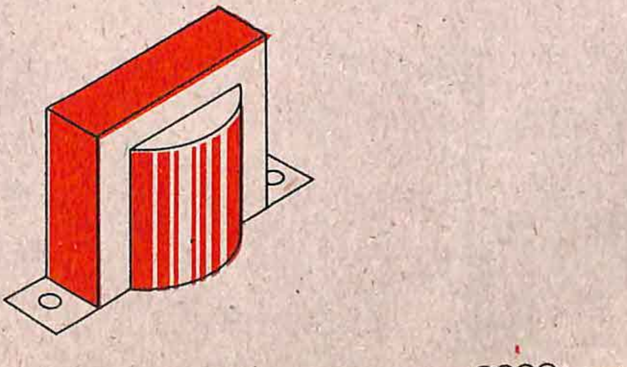
Inductance and inductive circuit components, such as inductors and transformers, have been described so far from the standpoint of their effects on circuits that contain *no* resistance. In any circuit, though, some resistance is present, even if it is only the resistance of the connecting wires and the transformer or inductor windings. When the circuit resistance is *very low* compared to any inductive reactance present, the resistance can often be ignored. Frequently, though, resistance is deliberately added to a circuit that contains inductance. Both the resistance and the reactance then affect the circuit current and must be considered in any analysis of the circuit.

RL Circuits Contain Resistors



Circuits that contain both resistance (R) and inductance (L) are called *RL circuits*. The relationships between the resistance and the inductance in RL circuits and their joint effect on circuit operation are covered in Volume 4.

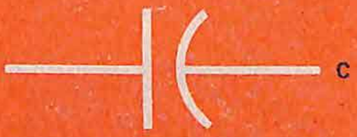
RL Circuits Contain Inductors



capacitance and the capacitor

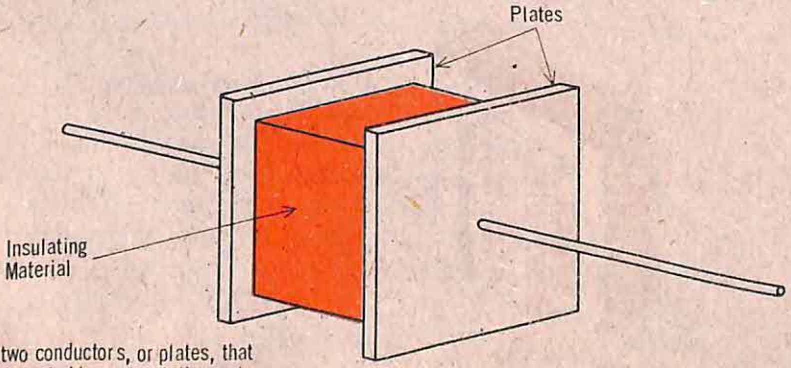
Capacitance may loosely be defined as the property of an electric circuit that enables it to store electric energy by means of an *electrostatic field* and to *release* this energy sometime later. Devices that introduce capacitance into circuits are called *capacitors*. Physically, a capacitor exists whenever an *insulating* material separates *two conductors* that have a difference of potential between them. Capacitors are items that are manufactured for deliberately adding capacitance to a circuit. Capacitance, however, can also be a byproduct of the arrangement and location of parts in an electric circuit or system. In this case, the capacitance they introduce is usually unwanted. In a capacitor, the electric energy is stored in the form of an electrostatic field between the two conductors, or *plates*, as they are usually called.

CAPACITORS can alternately **STORE** and **RELEASE** electrical energy by means of an **ELECTROSTATIC FIELD**



This is the symbol and letter designation for capacitors

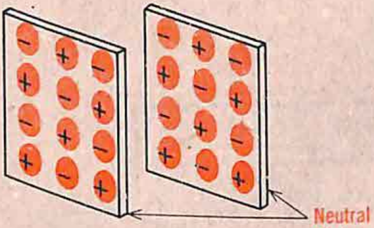
Capacitors used to be and are still sometimes referred to as *condensers*. The term capacitor, however, is more correct.



Any two conductors, or plates, that are separated by an insulating material can form a capacitor

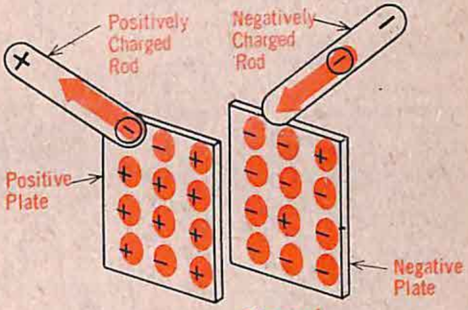
charging a capacitor

When a capacitor has a potential difference between its plates, it is said to be *charged*. To produce a potential difference, or in other words, to charge a capacitor, *free electrons* are made to *accumulate* on one plate, and at the same time free electrons are *removed* from the other plate. One plate thus has an *excess* of free electrons, and the other plate has a *lack* of them. Since electrons are negative, the plate with the excess electrons has an overall *negative* charge, while the plate from which electrons were removed has an overall *positive* charge. A difference of potential, or a voltage, therefore exists between the plates. This is shown for the case of a simple capacitor that has two metal plates separated by air, which acts as an electrical insulator. Before the capacitor is charged, both plates are electrically *neutral*. As you remember from Volume 1, this means that they contain an *equal number* of positive charges (protons) and negative charges (electrons).



Uncharged Capacitor

In an uncharged capacitor, both plates have an equal number of electrons and protons, and are, therefore, electrically neutral



Charged Capacitor

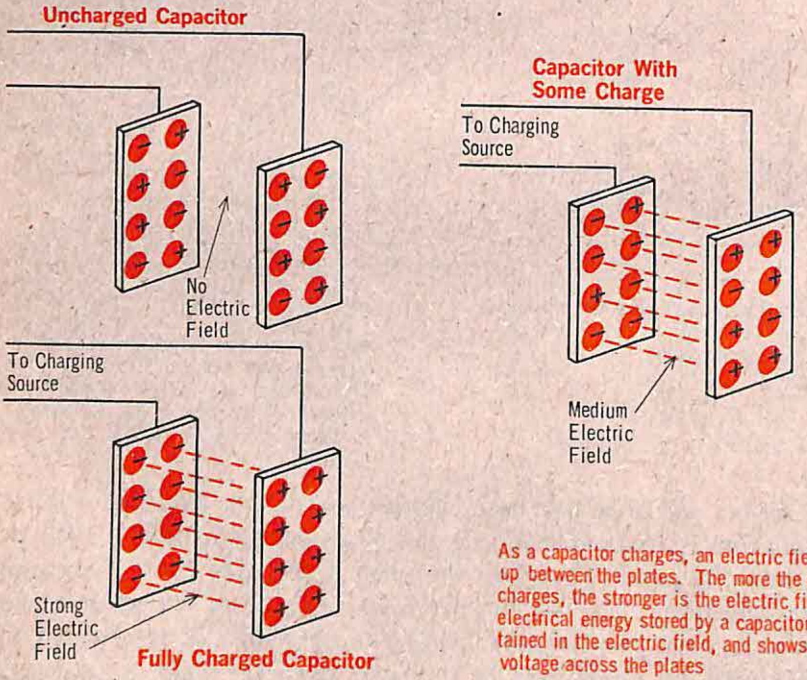
When a capacitor is charged, one plate is supplied with an excess of electrons, and is, therefore, negatively charged; meanwhile electrons are removed from the other plate, so that one is positively charged

If a rubber rod that has been charged negatively by being rubbed with cat's fur is touched to one plate, electrons from the rod will be drawn into the plate. The plate then has a negative charge, since it has more electrons than protons. If at the same time, a glass rod that has been charged positively by being rubbed with silk is touched to the other plate, electrons will be attracted from the plate by the rod. This plate then has a positive charge, because it has more protons than electrons.

In actual circuits, of course, capacitors are not charged by rubber and glass rods. Practical charging sources, such as batteries and generators, are used.

the electric field

When a capacitor is charged, one plate is negative and the other is positive. Since electrons are *attracted* by a *positive* potential, the excess electrons on the negative plate would tend to move to the positive plate were it not for the fact that the two plates are separated by an insulating material. Even though the electrons cannot flow to the positive plate, the *electrostatic force* that attracts them still exists. This force is called the *electric field,* and can be pictured as lines of electric force that exist between the two capacitor plates. The more a capacitor is charged, the stronger is the electric field. As the charges are increased, so also does the electric field and the force of attraction between the plates. In actual practice, a capacitor can be *overcharged* to the point where the attraction between the positive plate and the negative plate is so great that the electrons will be *pulled* through the insulation to the positive plate. When this happens, the insulation is said to have *broken down.*

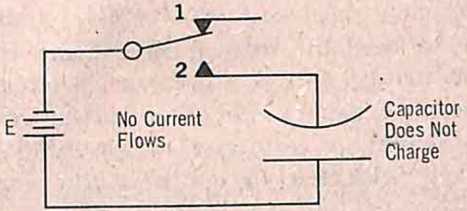


As a capacitor charges, an electric field is set up between the plates. The more the capacitor charges, the stronger is the electric field. The electrical energy stored by a capacitor is contained in the electric field, and shows up as a voltage across the plates

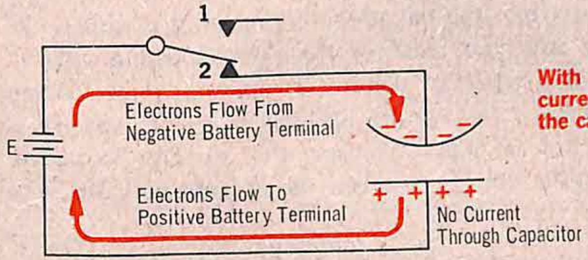
The electric field between the plates of a capacitor can be considered as *stored energy,* and it shows up as a *voltage* across the plates. The voltage will drop if the stored energy is released when the capacitor is discharged. This is covered later.

charging a capacitor in a d-c circuit

For a capacitor to become charged and thus store electrical energy, it must have a difference of potential, or voltage, applied to the plates. If this voltage is supplied by a battery, one plate of the capacitor is connected to the positive battery terminal, and the other plate, to the negative battery terminal. If a switch is placed in the circuit, as shown, no voltage is applied to the capacitor as long as the switch is open. Consequently, the capacitor plates are neutral, and no energy is stored.



With the switch open, position 1, no current flows in the circuit, and the capacitor does not charge


1
2
E
Electrons Flow From Negative Battery Terminal
– – – –
Electrons Flow To Positive Battery Terminal
+ + + +
No Current Through Capacitor

With the switch closed, position 2, current flows in the circuit to charge the capacitor

When the switch is closed, electrons flow from the negative battery terminal, which has a negative potential, to the capacitor plate to which it is connected. The plate thus acquires an excess of electrons, or a negative charge. At the same time, the positive battery terminal, which has a positive potential, attracts an equal number of electrons from the capacitor plate to which it is connected. This leaves the plate with a lack of electrons, or a positive charge.

While the capacitor is charging, therefore, electrons flow through the circuit wires and enter and leave the battery. In other words, current flows in the circuit. You should note carefully, though, that although current flows in the circuit, it does not flow through the capacitor. The current enters and leaves the capacitor, but the insulation between the capacitor plates prevents current from flowing through the capacitor.

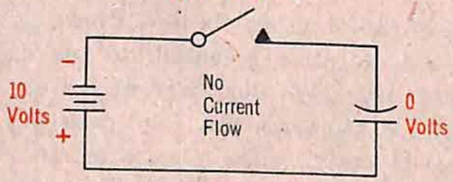
charging a capacitor in a d-c circuit (cont.)

As electrons flow into the negative plate of a capacitor and out of the positive plate, the increasing electrostatic field causes a voltage to be built up across the capacitor. This voltage starts at zero when the circuit is first closed, and increases as more and more electrons enter the negative plate and a like number leave the positive plate. The voltage building up across the capacitor has a polarity *opposite* to that of the battery supplying the current. As a result, the voltage across the capacitor *opposes* the battery voltage. The total circuit voltage, therefore, consists of two *series-opposing* voltages.

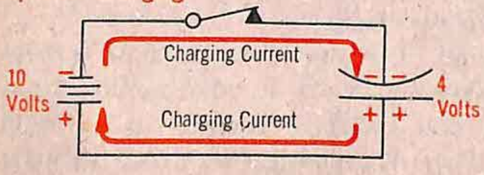
As the voltage across the capacitor increases, the *effective* circuit voltage, which is the *difference* between the battery voltage and the capacitor voltage, decreases. This in turn causes a decrease in circuit current. When the voltage across the capacitor *equals* the battery voltage, the effective voltage in the circuit is zero, and so current flow stops. At this point, the capacitor is *fully* charged, and no further current can flow in the circuit.

The current that flows while the capacitor is charging is called the *charging current*. From this you can see that the charging current and the voltage across the capacitor behave in *opposite* ways. When charging begins, the current is maximum and the capacitor voltage is zero. And as the capacitor voltage increases, the current decreases. Finally, when the capacitor voltage reaches its maximum value, the current is zero

Open Circuit

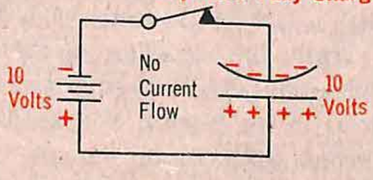


Capacitor Charging

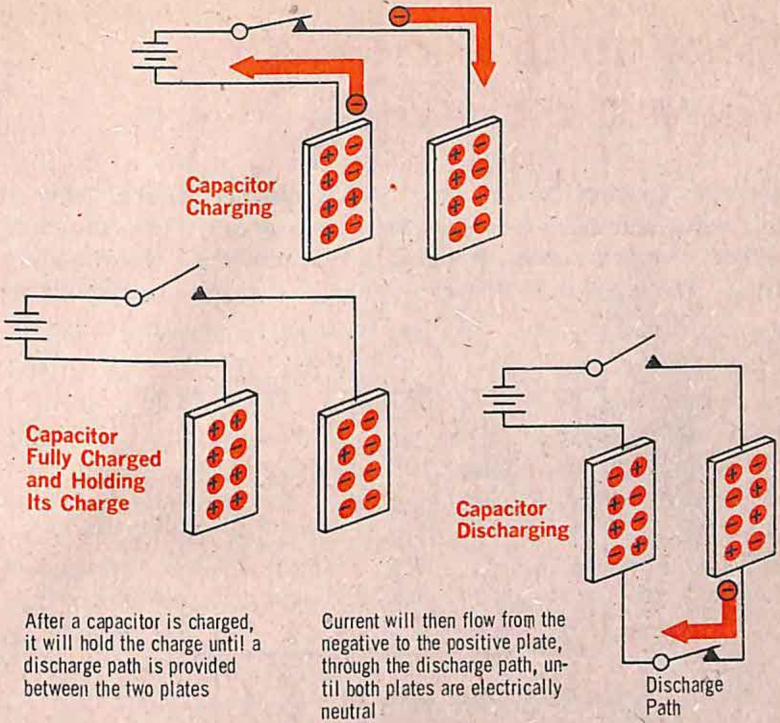


A capacitor charges until the voltage built up across it equals the applied voltage. When the two voltages are equal, the capacitor is fully charged, and current stops

Capacitor Fully Charged



For this reason, a capacitor can never be charged to a higher voltage than the source supplying the charging current



After a capacitor is charged, it will hold the charge until a discharge path is provided between the two plates

Current will then flow from the negative to the positive plate, through the discharge path, until both plates are electrically neutral

discharging a capacitor

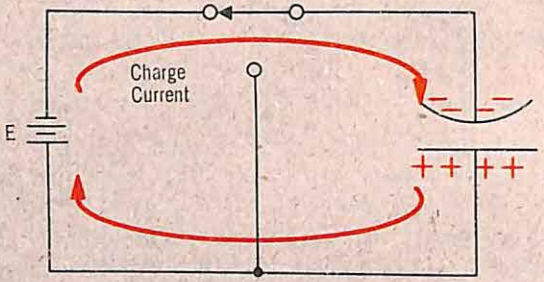
Once a capacitor is charged, it will theoretically hold the charge indefinitely. In practice, though, when a charged capacitor is removed from its charging source it will *eventually* lose its charge. This loss of charge takes time, however, and so for practical circuit applications, a capacitor can be considered as holding its charge until it is *deliberately* made to return the electrical energy stored in it. The recovering of this energy is referred to as *discharging the capacitor*.

To discharge a capacitor, all that is required is a *conducting path* between the capacitor plates. The free electrons on the negative plate will then flow to the positive potential of the positive plate. In this way, the positive plate acquires enough electrons to make it electrically neutral, and the negative plate loses enough electrons to make it neutral also. With both plates neutral, the capacitor has no voltage across it, and is said to be discharged. The flow of electrons from the negative to the positive plate during discharging makes up what is called *discharge current*. The path followed by this current is known as the *discharge path*.

discharging a capacitor in a d-c circuit

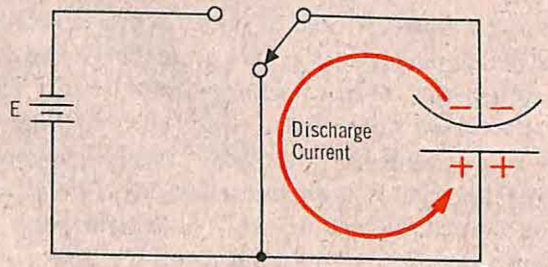
After a capacitor in a d-c circuit has charged to the value of the source voltage, current stops flowing in the circuit. Thus, the circuit is, in effect, an *open* circuit. It remains this way until the capacitor discharges. The capacitor *cannot* discharge through the power source, since the polarity of the source voltage is such that it opposes the capacitor voltage. For the capacitor to discharge, therefore, some other discharge path must be provided.

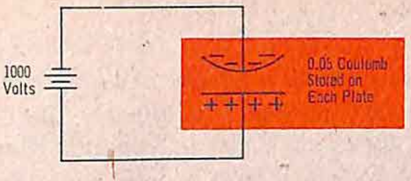
Charge Circuit



When such a path is available, the capacitor will *completely* discharge through it. During discharge, the capacitor and the discharge path can be considered as an independent circuit, with the capacitor supplying the voltage for the circuit. At the instant the capacitor begins to discharge, the voltage applied to this circuit, which is the voltage across the capacitor, is maximum. So also, therefore, is the current. As the capacitor discharges, both the voltage and current in the discharge circuit decrease, until finally they both reach zero when the capacitor is fully discharged.

Discharge Circuit





Capacitance is Measured in Farads

$C = Q/E$

$C = 0.05$ Coulomb/1000 Volts
$= 50$ Microfarads

unit of capacitance

Capacitance is a measure of *how well* a capacitor can *store* electrical charge. More exactly, the capacitance is proportional to the *amount of charge* (in coulombs) that is stored in the capacitor for each volt applied across it. Actually, the net charge stored in a capacitor is zero, since the two plates have equal charges of *opposite* polarities. Therefore, "the charge stored in a capacitor" means the charge stored on either one of the capacitor plates. If two capacitors each have 100 volts applied, and one stores 5 coulombs of charge on each plate, while the other stores 2 coulombs, the one storing 5 coulombs has the greater capacitance.

Also if both capacitors stored 5 coulombs, but one capacitor needed 100 volts applied to it, and the other only needed 50 volts, the one that required less voltage to get the same charge has a greater capacitance.

The unit of capacitance is the *farad,* named in honor of the scientist Michael Faraday. A capacitor has a capacitance of one farad, when with one volt applied to its plates, it stores one coulomb of charge on each of its plates. The equation for capacitance is

$$C = Q/E$$

where C is the capacitance given in farads, Q is the charge on one plate measured in coulombs, and *E* is the voltage applied to the capacitor.

In practice, the farad is an enormous storage capability. For this reason, fractional units of the farad are practically always used. These fractional units are the microfarad (μf) and the micromicrofarad ($\mu\mu$f), known as the picofarad (pf).

CONVERSION OF UNITS

1 farad (f) = 1,000,000 microfarads (μf) = 1,000,000,000,000 picofarads (pf)

1 microfarad (μf) = $\frac{1}{1{,}000{,}000}$ farad (f) = 1,000,000 picofarads (pf)

1 picofarad (pf) = $\frac{1}{1{,}000{,}000{,}000{,}000}$ farad (f)

1 picofarad (pf) = $\frac{1}{1{,}000{,}000}$ microfarad (μf)

1 picofarad (pf) = 1 micromicrofarad ($\mu\mu$f)

capacitive time constant

When a capacitor is connected to a source of d-c voltage, it charges very rapidly. If there was *no resistance* in the charging circuit, the capacitor would become fully charged almost *instantly*. Resistance has the effect of causing a delay in the time required for charging. And since, as you know, every circuit has some resistance, it takes some definite amount of time for a capacitor to become charged. The exact time required depends on both the resistance (R) in the charging circuit, and the capacitance (C) of the capacitor. The relationship between these two quantities and the charging time is expressed by the equation:

$$t = RC$$

where *t* is the *capacitive time constant*, representing the time required for the capacitor to charge to 63.2 percent of its fully-charged voltage. In each succeeding time constant, the voltage across the capacitor increases an additional 63.2 percent of the remaining voltage. Thus, after the second time constant (2t) the capacitor has charged to 86.4 percent of its maximum voltage, after 3t to 94.9 percent, after 4t to 98.1 percent, and after 5t to more than 99 percent. The capacitor is considered to be *fully charged* after a period of *five* time constants.

In a similar manner, the capacitive time constant also shows the time required for the voltage across a discharging capacitor to drop to various percentages of its maximum value.

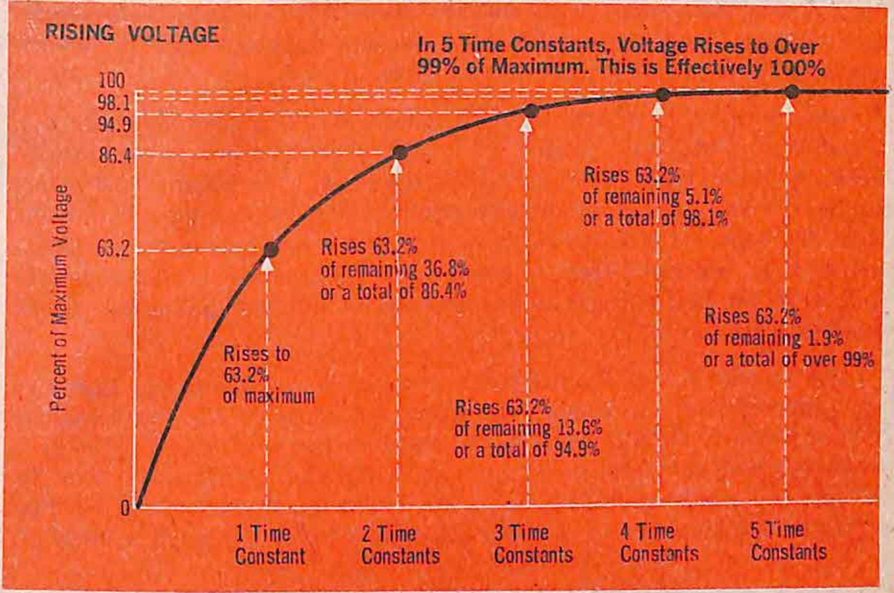
You have probably noticed a similarity between the capacitive time constant and the inductive time constant, which was described earlier. The similarity is that the voltage across a capacitor builds up and drops off in exactly the same way and at the same rate that current through an inductor rises and falls. This can easily be seen by comparing the curves shown on the following page with those for the inductive time constant given on page 3-60.

UNITS OF CAPACITIVE TIME CONSTANT

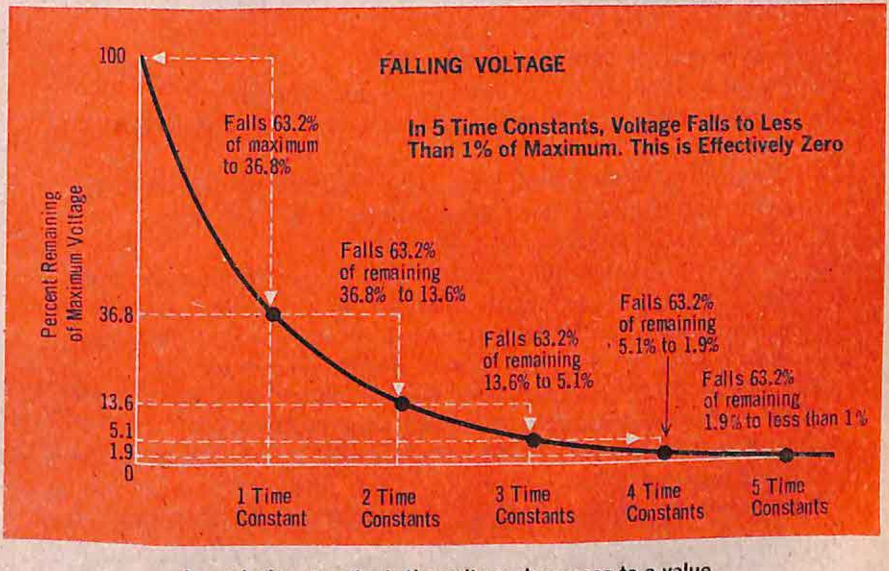
If R Is In	And C Is In	Then t Is In
Ohms	Microfarads	Microseconds
Kilohms	Microfarads	Milliseconds
Megohms	Microfarads	Seconds
Ohms	*Picofarads	Microseconds/1,000,000
Kilohms	Picofarads	Microseconds/1,000
Megohms	Picofarads	Microseconds

*Also known as micromicrofarad.

capacitive time constant (cont.)



In each time constant, the voltage increases to a value 63.2% closer to its maximum value



In each time constant, the voltage decreases to a value 63.2% closer to zero

summary

☐ Capacitance exists whenever two conductors are separated by an insulating material, and have a difference of potential between them. ☐ The basic unit of capacitance is the farad; however, practical units are the microfarad and the picofarad (also known as the micromicrofarad). ☐ Capacitors are devices that add capacitance into circuits. ☐ Capacitors can be charged by connecting batteries or generators across their plates.

☐ When a difference of potential, or a voltage, exists between the plates of a capacitor, it is said to be charged. ☐ A charged capacitor has an electrostatic force, or electric field, existing between the plates. The electric field stores energy. ☐ In a d-c circuit, although electrons flow through the circuit wires when the capacitor is being charged, they do not flow across the insulation between the capacitor plates. ☐ When a charged capacitor is allowed to lose its charge, the path followed by the electrons on discharging is known as the discharge path.

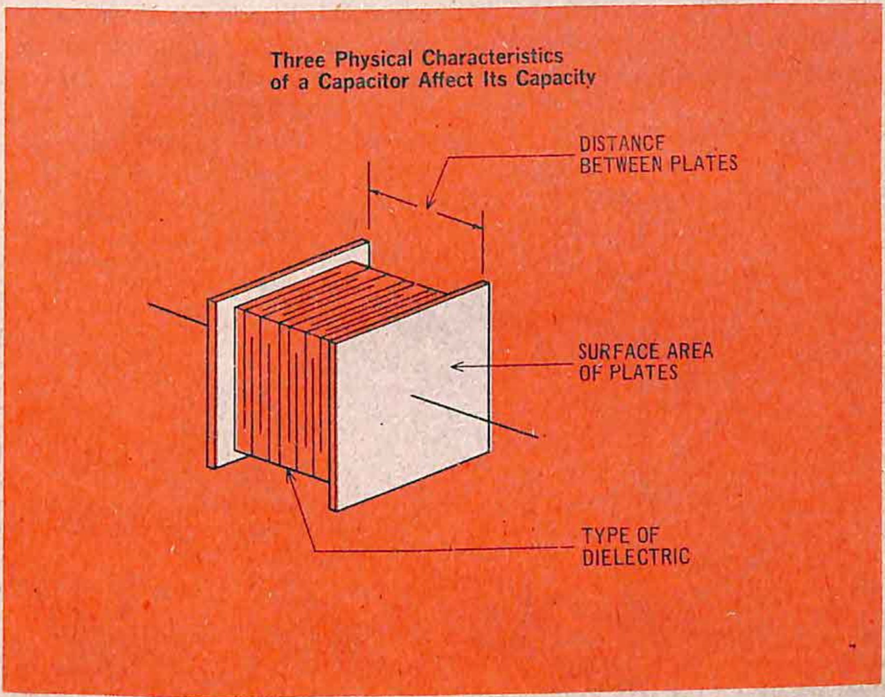
☐ The equation for capacitance is $C = Q/E$, where Q is the charge stored by the capacitor, and E is the voltage across the capacitor. ☐ The capacitive time constant in an RC circuit is expressed by the equation: $t = RC$. ☐ It takes five time constants to charge a capacitor from zero to more than 99 percent of its maximum charge. ☐ The waveform of the voltage build-up across a capacitor is similar to that of the current increase through an inductor.

review questions

1. How is energy stored in a capacitor?
2. Express 2 farads in picofarads; in microfarads.
3. Express 2 picofarads in microfarads. Express 2 farads in microfarads.
4. What is the capacitance of a capacitor that stores 5000 microcoulombs when the voltage across it is 1000 volts?
5. What is the *capacitive time constant*?
6. It takes 10 seconds for a capacitor to charge to the maximum voltage when it is applied in series with a resistor across a battery. What is the time constant of the circuit? How long does it take for the capacitor to discharge completely?
7. For the circuit of Question 6, what is the value of the capacitor if the resistor has a value of 5 megohms?
8. If R is in ohms and C is in microfarads, in what units is the time constant, t?
9. If t is in seconds and C is in microfarads, in what units is R?
10. If R is in megohms and t is in microseconds, in what units is C?

what controls capacitance values?

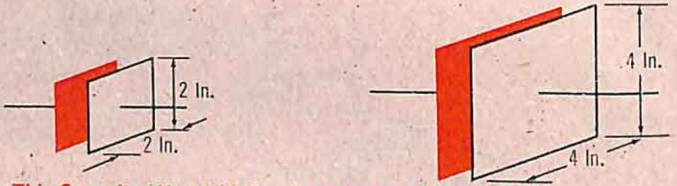
There are three factors that determine the capacitance of a capacitor. They are: (1) the *surface area* of the plates; (2) the *distance* between the plates; and (3) the insulating material, or *dielectric* as it is called, used between the plates. The amount of voltage applied to a capacitor, or the quantity of charge stored in it, have *no* effect on capacitance. This, of course, assumes that the capacitor is not connected to excessively high voltages, which could damage or destroy it.


Three Physical Characteristics
of a Capacitor Affect Its Capacity
DISTANCE BETWEEN PLATES
SURFACE AREA OF PLATES
TYPE OF DIELECTRIC

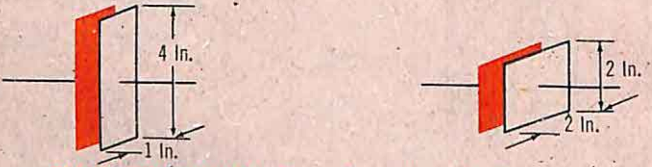
There are other factors which can affect capacitance, and which would have to be considered when selecting capacitors for certain applications. These factors include the frequency of the applied voltage, the temperature of the capacitor, and the age of the capacitor. Generally, these additional factors have only slight effects on capacitance, and can be ignored. At other times, though, they are very important and must be taken into consideration. More detailed information in this area is given later.

effect of plate surface area

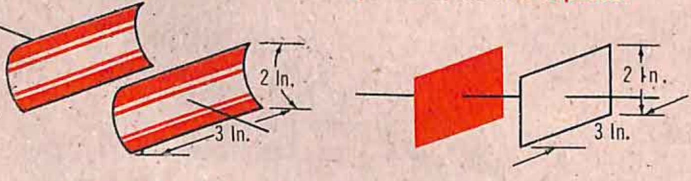
If two capacitors are made with the same dielectric and the same separation between their plates, but with different sized plates, the one with the *most* plate *surface area* will have the *greatest* capacitance. The reason for this is that the larger the plates are, the more charge can be stored on them. A large negative plate has more room to accumulate free electrons than does a smaller one. And a large positive plate has more free electrons to give up than does a smaller one. If the separation between plates and the dielectric is held constant, the capacitance of a capacitor is *directly proportional* to the surface area of the plates. Doubling the surface area results in a doubling of the capacitance. Likewise, if the surface area is cut in half the capacitance is halved. These characteristics only apply, of course, if the plates are completely aligned and parallel to each other.



This Capacitor Has 1/4 The Capacitance Of This Capacitor



This Capacitor Has The Same Capacitance As This Capacitor



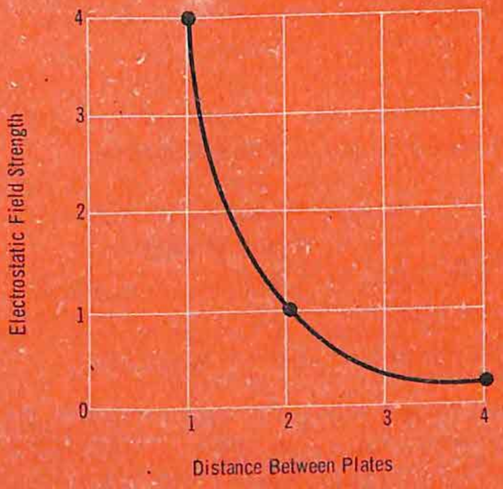
This Capacitor Has The Same Capacitance As This Capacitor

It was pointed out previously that the farad represents an enormous amount of stored charge, and that is why the units of microfarad and picofarad are used. As an example of the impractical nature of the farad, consider the plate area required for a 1-farad capacitor. If the separation between the plates is 1 millimeter and air is used as the dielectric, each plate would have to be approximately 6½ miles high by 6½ miles wide.

effect of plate separation

As you learned earlier, the capacitor charges because electrons accumulate on the negative plate, and leave the positive plate. Actually, the charges on each plate affect one another greatly. The greater the negative charge built up on the negative plate, the more electrons will be *repelled* off the positive plate; and the greater the charge on the positive plate, the more electrons will be *attracted* to the negative plate. In this way, the electrostatic field that is built up between the plates aids the source voltage. The stronger the field is for a given charge, the more it will aid the applied voltage.

If you think back to Volume 1, you should recall *Coulomb's Law of Electric Charges:* The strength of the electrostatic lines of force is inversely proportional to the *square* of the distance between the charges. This means that if two charged plates are moved apart so that the space between them is doubled, the strength of the electrostatic field will be reduced to 1/4 of what it was. And a weaker field will give *less aid* to the applied voltage; less electrons will accumulate on the negative plate and leave the positive plate.

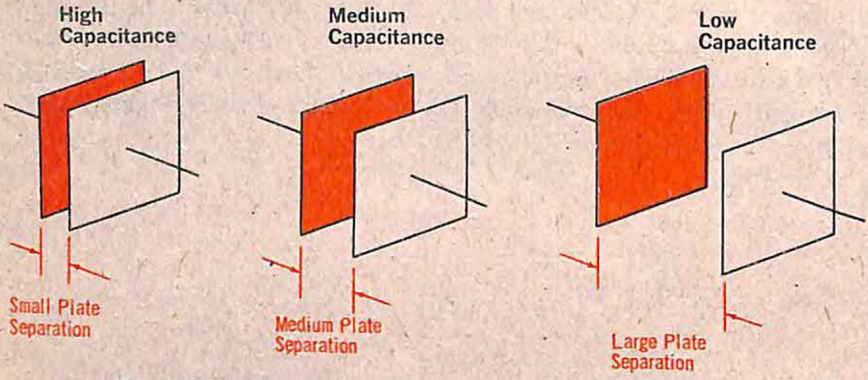


The strength of the electrostatic field is inversely proportional to the square of the distance. If the distance between the plates is halved, the strength will increase four times

Capacitance, therefore, is *inversely proportional* to the distance between the capacitor plates. This means that the smaller the distance between the plates, the greater is the capacitance. Conversely, the larger the distance between plates, the smaller is the capacitance.

effect of plate separation (cont.)

There is a *limit*, though, on how small the separation between plates can be made. If the plates are too close together, electrons will be *torn loose* from the negative plate by the potential on the positive plate. This *breakdown* can damage, and even destroy, the capacitor. Actually, the smallest spacing possible before breakdown occurs depends on the voltage across the capacitor, and the dielectric between the plates. Where high voltages are involved, breakdown will occur even in capacitors with large separations; low voltages will allow smaller separations. Some commercially available capacitors, however, have spacings as small as 0.0005 inch, and can withstand voltages of hundreds of volts.

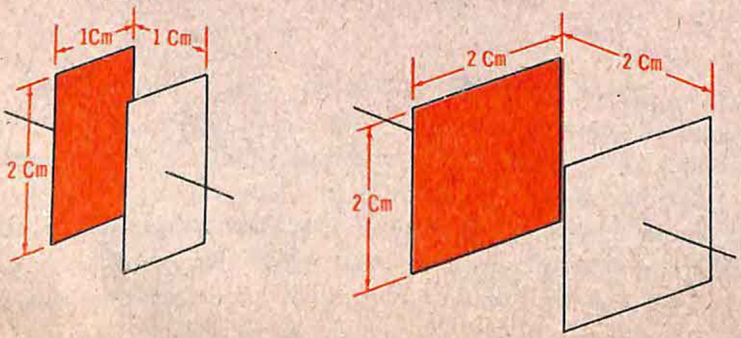


The capacitance of a capacitor is inversely proportional to the distance between the plates

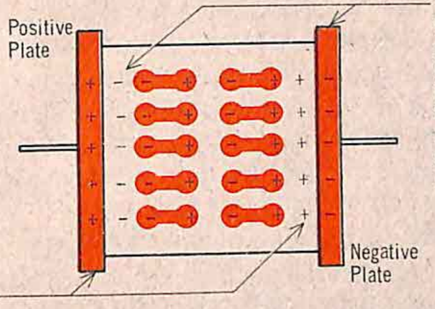
Without considering the effect of the dielectric, the following equation relates the capacitance to the area of the plates and the distance between them:

$$C = \frac{A \text{ (Area of the Plates)}}{d \text{ (Distance between Plates)}}$$

Using this equation, you can see that these two capacitors have the same capacitance value



effect of the dielectric



The positive end of the dielectric and the positive plate both attract electrons toward the negative plate. So, effectively, the positive charge is closer to the negative plate

The negative end of the dielectric and the negative plate both repel electrons from the positive plate. So, effectively, the negative charge is closer to the positive plate

Polar molecules align with the electrostatic field, effectively moving the charges on the plates closer together to increase capacitance

The insulating material used between the plates of a capacitor is called a *dielectric*. The dielectric can be air, glass, paper, or even a vacuum. In fact, any *insulating* material will work, but some produce a high capacitance, and, therefore, are good dielectrics, while others yield a low capacitance, and so are poor dielectrics.

The difference between good and poor dielectrics can be explained on the basis of how easily the molecules of the dielectric are affected by electrostatic forces. Many insulating materials have molecules whose orbiting electrons are unsymmetrically located. One side of the molecule has more electrons than the other, and so in effect, the molecule has a negative side and a positive side. These are called *polar molecules*. They have a net charge of zero because there is an equal number of electrons and protons; but because of a lopsided accumulation of electrons, the molecule has a positive pole and a negative pole.

When such a dielectric is inserted between the plates of a charged capacitor, one side of the dielectric is exposed to the positively charged plate, and the other side to the negatively charged plate. The polar molecules in the dielectric are attracted to the charged plates. As a result, the molecules *align* themselves with their positive poles towards the negative plate and their negative poles towards the positive plate. An electrostatic force then exists between each end of the dielectric and the nearest plate. The direction of these forces is such that the negative end of the dielectric repels electrons from the positive plate, and in doing so aids the negative plate, which is doing the same thing. Similarly, the positive end of the dielectric attracts electrons to the negative plate, and so aids the positive plate. Effectively, then, the dielectric moves the charges on the capacitor plates *closer together*, and, as you have learned, this results in increased capacitance.

dielectric constant and strength

Since the dielectric material has a significant effect on the capacitance value of a capacitor, it is often convenient to compare various materials from the standpoint of how well they perform as dielectrics. For this purpose, a rating system is used in which the dielectric properties of materials are related to those of *air*. Actually, the system is based on the dielectric properties of a pure *vacuum*. However, there is so little difference between an air dielectric and a vacuum dielectric, that for all practical purposes they can be thought of as identical.

In this system, air is assigned the value of 1. The other materials are assigned values which indicate how much more effective they are as dielectric materials than is air. For example, a capacitor with a dielectric material whose value is 5 will have five times the capacitance of a similar capacitor having an air dielectric. The value of each material is called the *dielectric constant* of that material. The dielectric constant is usually designated by the letter K. Therefore, to see the relationship of all the physical properties of a capacitor compared to its capacity, the following equation can be used:

$$C = K \frac{A \text{ (plate area)}}{d \text{ (plate spacing)}}$$

In addition to its dielectric constant, each material also has a property called its *dielectric strength*. This indicates the *maximum* voltage that can be applied across the dielectric *safely*. If the voltage is exceeded, the molecules of the dielectric material break down, and arcing occurs between the dielectric and the capacitor plate. Dielectric strength is expressed as a maximum allowable voltage for a specific thickness of material.

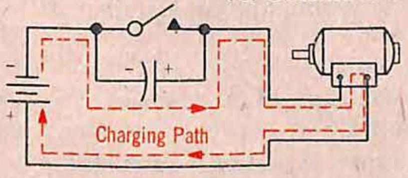
DIELECTRIC CONSTANTS		DIELECTRIC STRENGTHS	
Material	**Dielectric Constant (K)**	**Material**	**Dielectric Strength (Volts/0.001 in.)**
Air	1	Air	80
Resin	2.5	Fiber	50
Hard Rubber	2.8	Glass	200
Dry Paper	3.5	Castor Oil	370
Glass	4.2	Bakelite	500
Bakelite	4.5 to 7.5	Porcelain	750
Mica	5 to 9	Paper (paraffined)	1200
Porcelain	5.5	Paper (beeswaxed)	1800
Mycalex	8	Mica	2000
Titanium Dioxide Compounds	90 to 170		

capacitive d-c circuits

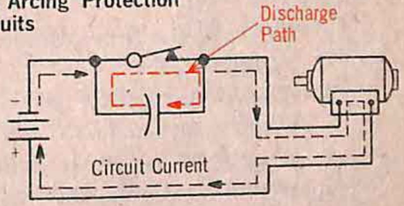
A d-c circuit that contains only capacitance behaves quite differently than a d-c circuit containing only resistance or inductance. Both resistance and inductance *oppose* circuit current, although in different ways. Capacitance, on the other hand, *prevents* d-c current flow, once the initial charging current has charged the capacitor. Capacitors are, therefore, said to *block* dc. You can see, then, that there are not a great many applications for capacitors in d-c circuits. This does not mean that capacitors are never used in d-c circuits. There are many d-c applications for which capacitors are well suited. One of these is to prevent arcing across the contacts of electric switches, as shown. When a switch opens a circuit in which a large current is flowing, the current attempts to continue flowing. This causes arcing across the switch contacts, which can eventually ruin the switch. A capacitor connected across the switch contacts provides a path for current flow until the switch is fully open and the danger of arcing is passed.

Capacitors are also used with batteries to supply large current for a very short time, which the battery alone could not supply. With the battery connected across the capacitor, the battery could supply a safe low level of current over a long period to charge the capacitor. Then, if the capacitor is connected to, say a photoflash lamp, it could discharge very quickly and supply a higher value of current than the battery could in such a short time.

Capacitors Can Provide Arcing Protection For Switches In D-C Circuits

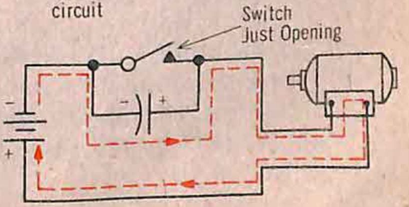


When the switch is open, the capacitor is charged to the source voltage



When the switch is closed, the capacitor discharges through the switch contacts. While the switch is closed, the capacitor stays in the discharged condition (both plates neutral), and has no effect since it is shorted out of the circuit

If it was not for the capacitor, at the instant the switch opened, the voltage across the switch contacts would exceed the dielectric strength of the small air mass between the open contacts. Arcing would then result. The capacitor, though, provides a low-resistance path around the contacts. The current, therefore, flows through the capacitor instead of across the air gap until the capacitor is charged



summary

☐ The capacitance of a capacitor is determined by three factors: the surface area of the plates, the distance between the plates, and the insulating material used between the plates. ☐ The effects of the three factors determining capacitance are expressed in the equation: $C = KA/d$. The equation shows that capacitance is directly proportional to the surface area of the plates, and inversely proportional to the distance between the plates. ☐ Other factors, such as frequency of applied voltage and temperature and age of the capacitor can affect capacitance. Usually, though, their effects are slight.

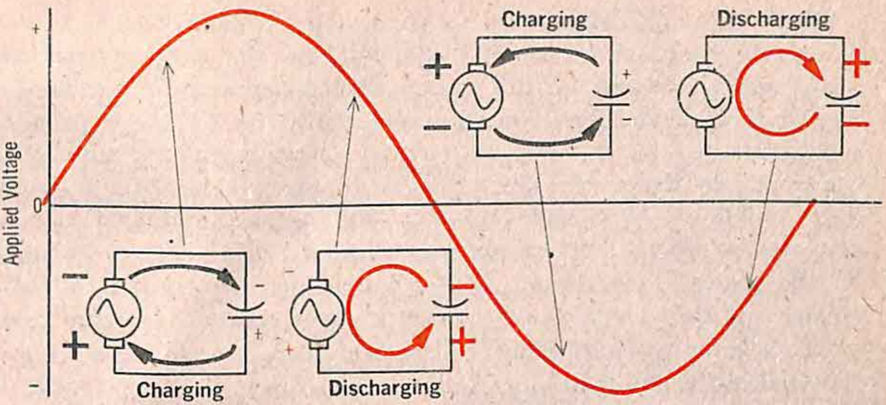
☐ The insulating material used between the plates of a capacitor is called the dielectric. ☐ A good dielectric increases capacitance by effectively moving the plates of the capacitor closer together. ☐ The dielectric constant, K, indicates how effective a material is as a dielectric. ☐ A system of comparing the dielectric constants of various materials is used in which air serves as a reference with a dielectric constant of 1. ☐ The maximum voltage that can be applied across a dielectric is called the dielectric strength.

☐ In d-c circuits, charged capacitors prevent d-c current flow. Capacitors are therefore said to block dc. ☐ Capacitors are also used to supply large currents for short intervals.

review questions

1. What are the three factors that determine the capacitance of a capacitor?
2. Why are dielectrics used in capacitors?
3. What is meant by the *dielectric strength* of a material?
4. What is meant by *dielectric constant*?
5. Which has the larger dielectric constant: air or hard rubber? Air or glass?
6. What happens to the capacitance of a capacitor if its plate area is doubled, and the distance between plates is halved?
7. If, in a capacitor, the dielectric constant is doubled without changing the plate area, how can the plates be adjusted so that the capacitance remains the same?
8. If the voltage applied across a capacitor is doubled, what happens to the capacitance?
9. How are capacitors used in a photoflash lamp?
10. Why are capacitors said to block dc in a d-c circuit?

capacitive a-c circuits



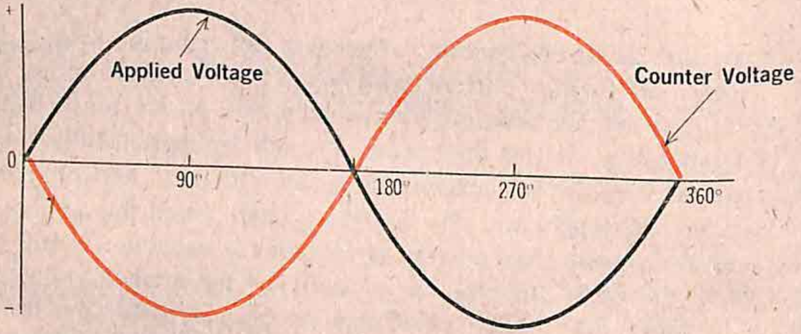
When a capacitor is connected to an a-c source, it alternately charges and discharges, first in one direction and then the other

A capacitor blocks dc. Therefore, once it is fully charged by an applied d-c voltage, no further current will flow in the circuit unless some means is provided for discharging the capacitor. In an a-c circuit, the applied voltage, as well as the current it produces, periodically changes direction. As a result, a capacitor in an a-c circuit is first charged by the voltage being applied in one direction. Then, when the applied voltage starts to decrease, less current flows, but the capacitor is still being charged in the same direction. As a result, as the applied voltage continues to drop, the voltage developed across the capacitor becomes greater. The capacitor, then acts as the source, and starts *discharging.* The capacitor becomes fully discharged when the applied voltage drops to zero and reverses its direction. Then the capacitor starts charging again, but in the same direction in which it was previously discharging. This continues until the applied voltage again starts to drop, and the events repeat themselves. This alternate charging and discharging, first in one direction, and then in the other, occurs during every cycle of the applied ac. An a-c current, therefore, flows in the circuit *continuously.* It can be said, then, that although a capacitor blocks dc, it *passes* ac.

The charging a path for a capacitor in an a-c circuit is from the negative terminal of the source to one capacitor plate, and from the other plate to the positive terminal of the source. The discharge path for the capacitor is from the negative plate, through the power source, and back to the positive plate. Remember, though, that in an a-c circuit, the terms positive plate and negative plate refer to a specific instant of time.

voltage relationships

When an a-c voltage source is connected across a capacitor, the amount of *charge* on the capacitor plates follows the sine-wave pattern of the applied voltage. At the instant the applied voltage is zero, no current flows, and so no charging potential exists for the capacitor; both plates are neutral. As the voltage source begins its sinusoidal rise from zero, the current flows, and the charge on the capacitor plates starts building. The charge continues building as the applied voltage increases. When the applied voltage reaches its peak value, the charge on the plates is maximum. This relationship between the applied voltage and the charge on the capacitor plates continues for the complete cycle of applied voltage. They both decrease and reach zero simultaneously, and then increase to a maximum in the opposite direction. Finally, both decrease again, reaching zero simultaneously.



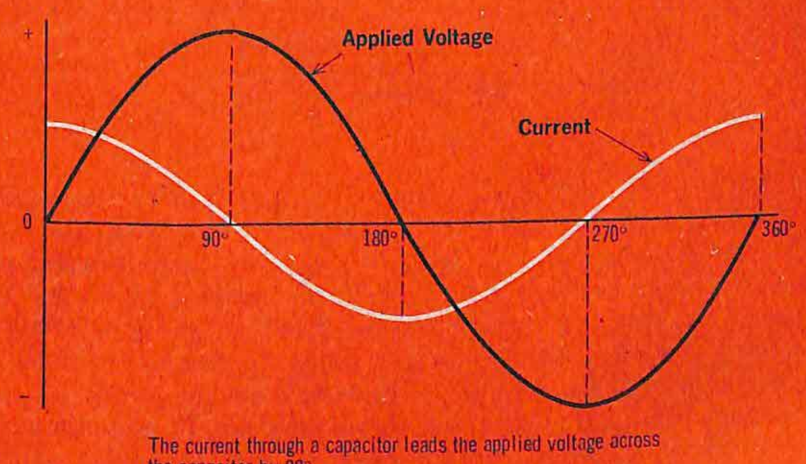
The counter voltage developed across a capacitor by the accumulation of charges on the capacitor plates is 180° out of phase with the voltage applied across the capacitor

The charges on the plates produce an electrostatic field that shows up as a voltage across the capacitor. This charge voltage follows the applied voltage exactly. If you measure the waveform pattern across the source and compare it to the pattern across the capacitor, you will see that they are the same. Actually, this has to be so, because when you measure one, you automatically must measure the other, since they are considered across one another. Since the charge on the capacitor plates follows exactly the same sine wave pattern as the applied voltage, you might think they are in phase. However, the charge on the capacitor actually *opposes* the applied voltage, so they are out of phase. Since the capacitor develops its own voltage, it acts as a voltage source that tries to cause current to flow into the battery. The capacitor voltage, therefore, is often called a *counter voltage* because it acts 180 degrees out of phase with the applied voltage.

voltage and current relationships

When an a-c voltage source is connected across a capacitor, *maximum* current flows in the circuit the instant the source voltage begins its sinusoidal rise from zero. At first it may seem strange to you that maximum current flows when the source voltage is at its lowest value. But if you remember what you learned earlier for d-c circuits, this current is actually the movement of free electrons from the negative terminal of the source to one capacitor plate and from the other plate to the positive terminal of the source; as a result, maximum current would occur at this time, since the plates are neutral and present *no opposing* electrostatic forces to the source terminals. Therefore, as you can see by Ohm's Law, if the opposition to current flow is very, very low, a small applied voltage can cause considerable current to flow.

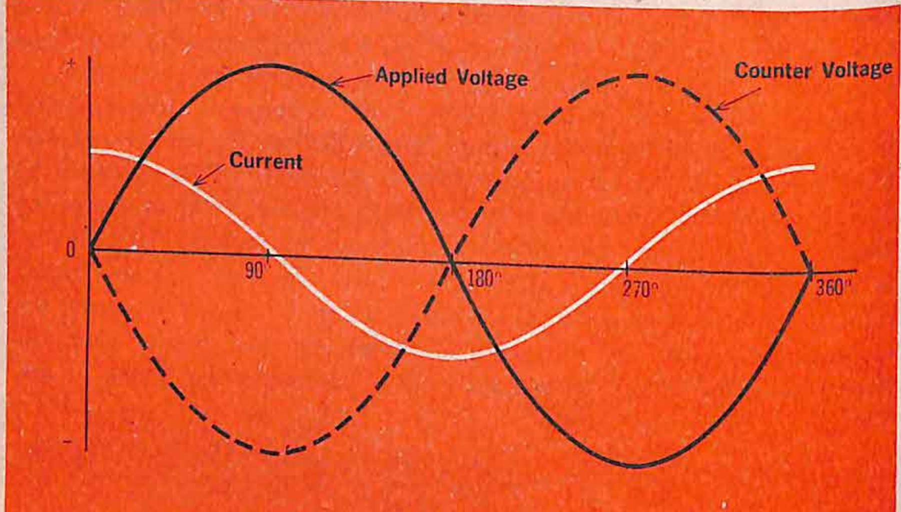
As the source voltage rises, however, the charges on the capacitor plates, which result from the current flow, build up. The charge voltage, then, presents an *increasing opposition* to the lower voltage and so the current *decreases*. When the source voltage reaches its peak value, the charge voltage across the capacitor plates is maximum. This charge is sufficient to completely *cancel* the source voltage, and so current flow in the circuit stops. As the source voltage begins to decrease, the electrostatic charge on the capacitor plates becomes greater than the potential of the source terminals, and so the capacitor starts to discharge.



The current through a capacitor leads the applied voltage across the capacitor by 90°

voltage and current relationships (cont.)

Electrons flow from the negative plate to the negative source terminal (which is becoming less negative), while an equal number of electrons flow from the positive source terminal (which is becoming less positive) to the positive plate. This direction of electron flow is *opposite* to the direction taken by the electrons during capacitor charging. Thus, at the point that the applied voltage passes through its maximum value and begins decreasing, the current in the circuit passes through zero and changes direction. As can be seen from the graph this constitutes a 90-degree phase difference, with the current *leading* the applied voltage. This 90-degree difference is maintained throughout the complete cycle of applied voltage. When the applied voltage has dropped to zero, the circuit current has increased to its maximum in the opposite direction; and when the voltage reverses direction, the current begins decreasing. Therefore, the *voltage* applied to a capacitor is said to *lag* the *current* through the capacitor by 90 degrees. Or, the *current* through a capacitor *leads* the applied *voltage* by 90 degrees. And, since the counter voltage is 180 degrees out of phase with the applied voltage, the current *lags* the counter voltage by 90 degrees.



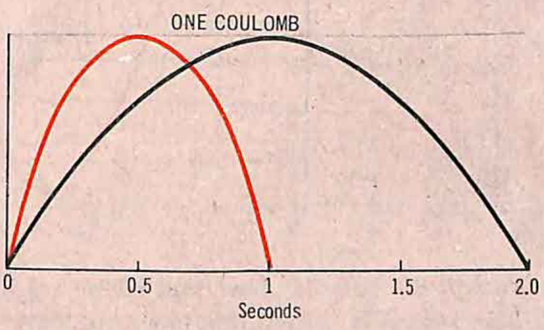
Current through a capacitor is 90° out of phase with both the applied voltage and the counter voltage. The current leads the applied voltage by 90° and lags the counter voltage by 90°

effect of frequency on capacitor current

Current flow in an a-c capacitive circuit is made up of free electrons flowing between the terminals of the voltage source and the plates of the capacitor. The electrons flow in one direction while the capacitor is charging, and in reverse direction during the time the capacitor discharges and charges in the opposite direction. The *amount* of *current* flow, you will remember from Volume 1, is determined by the *number* of *electrons* that flow past any point in the circuit in a unit *time*. Put another way, current is equal to the rate of electron flow. As an equation, this can be shown as

$$I = Q/t$$

where Q is the number of electrons being transported in time t.



Since an ampere is one coulomb of electrons per second, a frequency that allows one coulomb to flow in 0.5 second produces 2 amperes of current, while a frequency that allows one coulomb to flow in 1 second produces 1 ampere

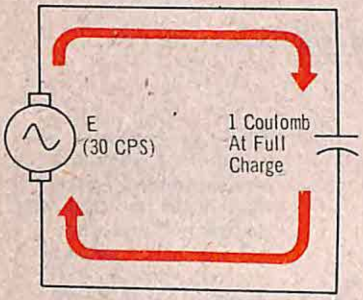
When an a-c voltage is applied to a capacitor, the capacitor alternately charges and discharges (in both directions) during every cycle of the applied voltage. For any given capacitor, the time required to reach maximum charge depends on the frequency of the applied voltage. The reason for this is that, as you already know, the charge on a capacitor follows the applied voltage exactly. Each time the applied voltage is maximum, the capacitor is at peak charge. And the higher the frequency, the faster the applied voltage rises from zero to maximum. So it follows that the higher the frequency, the faster the capacitor will reach its peak charge.

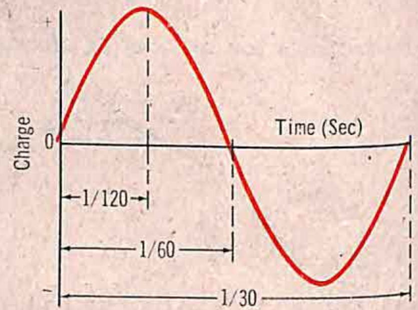
The amount of charge stored is independent of frequency; it depends only on the capacitance of the capacitor and the amplitude of the applied voltage. You can see, then, that two *identical capacitors* connected to *identical voltage* sources, which have *different frequencies*, will have *equal* values of Q but *different* values of t in the equation $I = Q/t$.

effect of frequency on capacitor current (cont.)

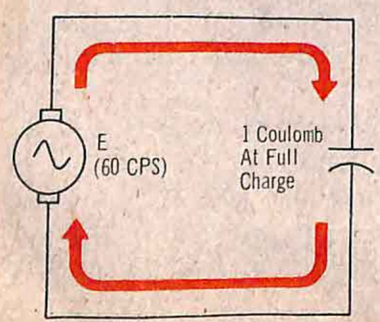
The currents through the two capacitors will therefore be different; although the same *number* of electrons flow, they flow *faster* in one capacitor than in the other, producing a greater current. The *higher frequency* (lower t) causes the *greater current*, and the *lower frequency* (higher t) causes the *lesser current*.

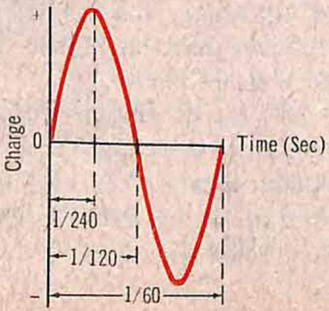
In summary, current through a capacitor is *directly proportional* to the frequency of the applied voltage. High frequencies result in large currents, whereas low frequencies produce small currents in the same capacitor.





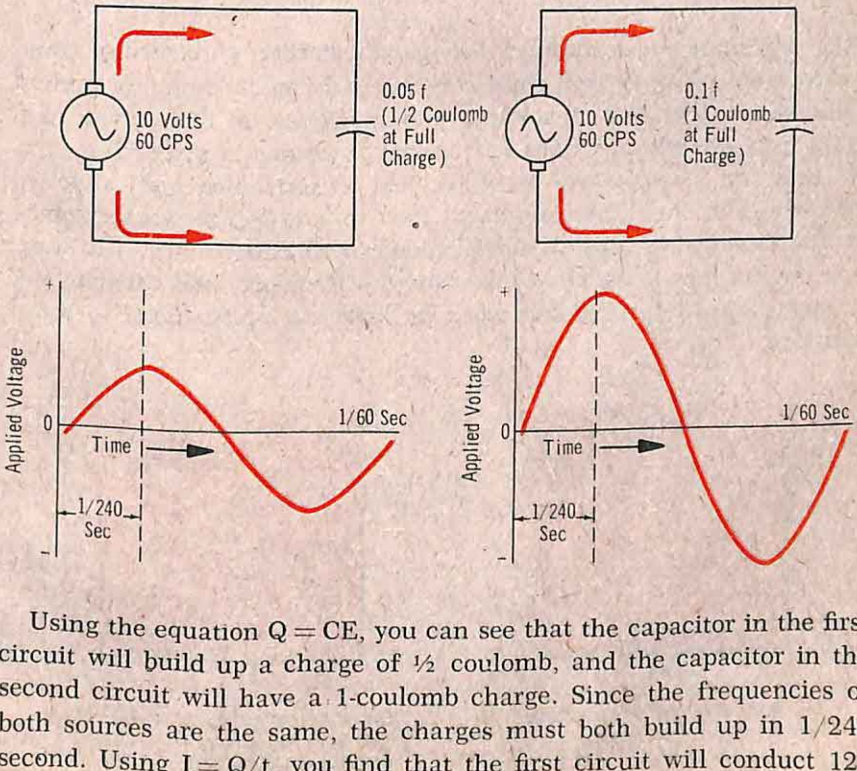
Assume that the capacitors in the circuits above and below are identical, and the source voltages have the same amplitude, but have the different frequencies as shown. Both capacitors would reach a maximum charge of 1 coulomb, and would discharge this amount during the cycle. For the charge to build up from zero to 1 coulomb with the 30-cps voltage, it would take 1/120 of a second. The formula for current ($I = Q/t$) gives a current flow of 120 amperes. However, for the capacitor to build up a 1 coulomb charge with the 60-cps voltage, it would take 1/240 of a second. This is 240 amperes of current flow.





effect of capacitance on capacitor current

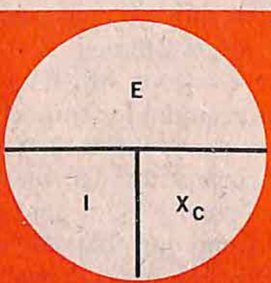
As you learned, capacitance is the amount of charge stored in a capacitor for each volt applied across the capacitor; or $C = Q/E$. Since this is the case, the *total charge* stored is equal to the capacitance times the applied voltage; or $Q = CE$. Thus, if equal voltages are applied across two capacitors that have different values of capacitance, the charges stored in the capacitors will be different. The capacitor with the larger capacitance will store the larger charge. This means that with the larger capacitance, more free electrons will flow during the charge and discharge cycles. If the times required for fully charging the two capacitors were the same, which would be the case if the applied voltages had the same frequency, the current through the capacitor with the larger capacitance would be greater than the current through the other capacitor. You can see from this that the current through a capacitor is *directly proportional* to the capacitance.



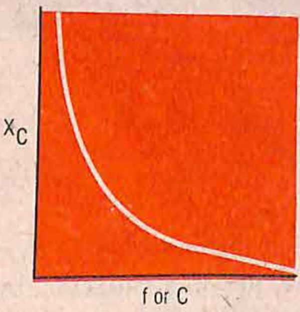
Using the equation $Q = CE$, you can see that the capacitor in the first circuit will build up a charge of ½ coulomb, and the capacitor in the second circuit will have a 1-coulomb charge. Since the frequencies of both sources are the same, the charges must both build up in 1/240 second. Using $I = Q/t$, you find that the first circuit will conduct 120 amperes and the second circuit will conduct 240 amperes.

capacitive reactance

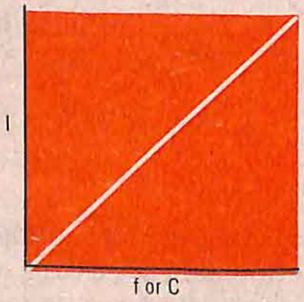
A capacitor offers *opposition* to the flow of a-c electric current similar to a resistor or an inductor. You know that the amount of a-c current that a capacitor conducts depends on the *frequency* of the applied voltage and the *capacitance*. The amplitude of the applied voltage, of course, also controls the value of current, but if the voltage amplitude were kept constant, the current would change whenever the frequency or the capacitance was changed. As you saw earlier, current flow could be calculated using certain equations, but it is much more convenient to use Ohm's Law. But capacitance and frequency, in themselves, cannot be used directly in Ohm's Law. What is needed is some characteristic that can be expressed in ohms, just as resistance and inductive reactance. The *opposition* to current flow in a capacitor is used, since the opposition also depends on frequency and capacitance. However, since current flow is *directly proportional* to frequency and capacitance, the opposition to current flow must be *inversely proportional* to these quantities.



In a purely capacitive circuit, capacitive reactance has the same effect as resistance in either a d-c circuit or an a-c resistive circuit



The decrease in capacitive reactance with increases in either frequency or capacitance is nonlinear. Thus, each additional increase in frequency or capacitance results in a smaller decrease in X_C



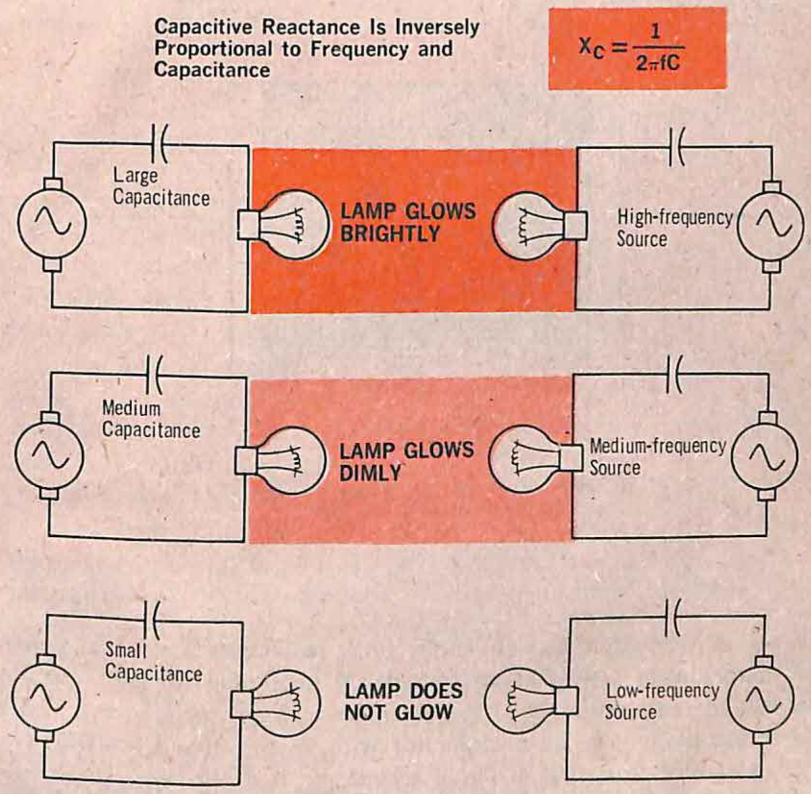
Current through a capacitor, on the other hand, increases linearly with increasing frequency or capacitance

capacitive reactance (cont.)

The opposition offered to the flow of current by a capacitor is called *capacitive reactance*, and is abbreviated X_C. Capacitive reactance can be calculated by:

$$X_C = \frac{1}{2\pi fC}$$

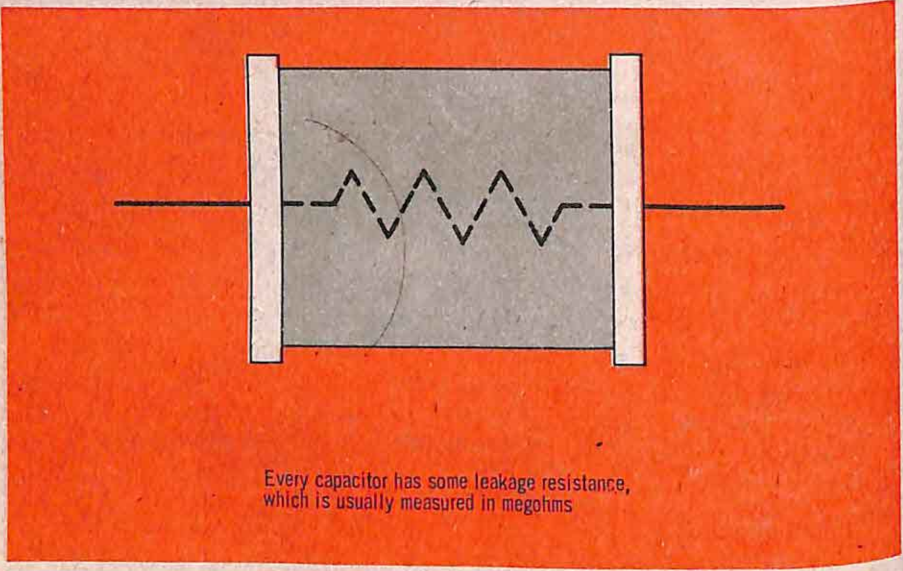
where 2π is approximately 6.28; f is the frequency of the applied voltage in cycles per second; and C is the capacitance in farads. You can see that the higher the frequency, or the greater the capacitance, the less will be the capacitive reactance. Like its inductive counterpart, inductive reactance, capacitive reactance is expressed in *ohms*, and acts just like a resistance in limiting a-c current flow. When you know the capacitive reactance, you can find current by:


Capacitive Reactance Is Inversely Proportional to Frequency and Capacitance

$$I = E/X_C$$

leakage resistance

Theoretically, the current that flows in a pure capacitive circuit results from the charge and discharge currents of the capacitor. The dielectric, which is an insulator, should prevent any current flow between the plates, except when breakdown occurs because of too high an applied voltage. However, there is no such thing as a perfect insulator. Even the best dielectric tends to conduct current to some degree. The dielectric, then, has some high value of resistance, known as *leakage resistance,* which allows some *leakage current* to flow. The leakage resistance tends to reduce the capacitance value.

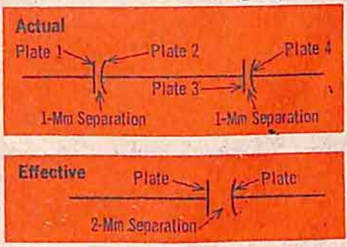


Every capacitor has some leakage resistance, which is usually measured in megohms

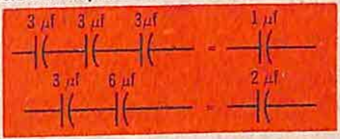
In a good capacitor, though, the leakage resistance is generally measured in megohms, and can be considered negligible for most applications. As the capacitor ages, however, the leakage resistance could reduce to the point where the capacitor will act just like a resistor. Generally, you will find that leakage resistance is lower with high-value capacitors than it is with low-value capacitors. The reason for this is that the larger capacitors have larger plate areas that are closer together. Therefore, their dielectrics must have large areas and be thin. And, as you learned in Volume 2, resistance goes down as the cross-sectional area is increased and the length, or thickness, is decreased. So, the larger the capacitor, the lower the leakage resistance, and the higher the leakage current.

series capacitors

Putting Capacitors In Series Decreases Capacitance



Series capacitors act as a single capacitor with a separation between their plates equal to the sum of the separations of the individual capacitors. The total capacitance is, therefore, less than that of any of the individual capacitors



The total capacitance of series capacitors is calculated the same as the total resistance of parallel resistors. The reciprocal method:

$$C_{TOT} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots + \text{etc.}},$$

or any of the shorter, special methods can be used. The total capacitive reactance, though, is simply the sum of the individual reactances:

$$X_{C\ TOT} = X_{C1} + X_{C2} + X_{C3} + \ldots + \text{etc.}$$

To obtain a desired value of capacitance, capacitors are often connected in series. The total capacitance of the series combination is *less* than the capacitance of any individual capacitor. The reason is that the series combination acts as a *single* capacitor, with a separation between its plates equal to the *sum* of the *separations* of the individual capacitors. And, as you have previously learned, the larger the separation between the plates, the lower is the capacitance.

The total capacitance of *series capacitors* is calculated the same way as the total resistance of *parallel resistors* (Volume 2). The total capacitive reactance of series capacitors, however, is not found in the same way. Since capacitive reactance is inversely proportional to capacitance, if the total capacitance of series capacitors goes down, then the reactance goes up. Actually, the individual reactances of the series capacitors are added just like series resistors. The total reactance can also be found by first determining the total capacitance of the series combination, and then calculating the reactance of the total capacitance.

The voltage drop across each individual capacitor of a series combination is *directly proportional* to the *reactance* of that capacitor. The voltage drop can be calculated by the equation $E = IX_C$, where I is the series circuit current, which is the *same* through each capacitor of the combination, and X_C is the reactance of the particular capacitor. Since voltage drop is directly proportional to capacitive reactance, which, in turn, is inversely proportional to capacitance, the voltage drop is also *inversely proportional* to the *capacitance*. Thus, in a series combination, the capacitor with the lowest capacitance has the largest voltage drop across it.

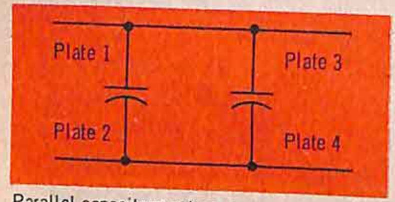
parallel capacitors

When capacitors are connected in *parallel,* the total capacitance is equal to the *sum* of the individual capacitances. The reason for this is that parallel capacitors act as a single capacitor having a *plate area* equal to the sum of the plate areas of the individual capacitors. With a larger plate area, therefore, the capacitance is increased. As a result, the total capacitance of parallel capacitors is found by taking the sum of the individual capacitances, just as with series resistors. The total capacitive reactance of parallel capacitors, on the other hand, goes in the other direction. The total reactance, then, is found by treating the individual reactances like parallel resistors; or it can be found by first determining the total capacitance and then finding the reactance of this total capacitance.

As is the case with parallel resistors and parallel inductors, the same voltage is dropped across each capacitor of a parallel combination, but the current through each differs for different capacitance values.

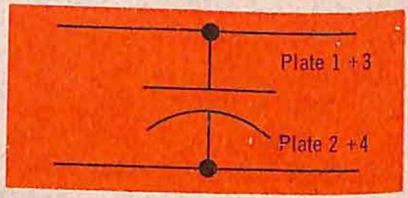
Putting Capacitors in Parallel Increases Capacitance

Actual

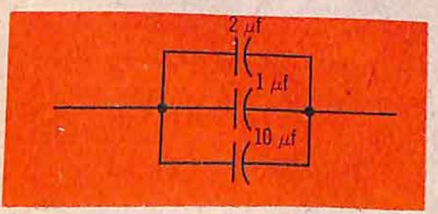


Parallel capacitors act as a single capacitor with a plate area equal to the sum of the plate areas of the individual capacitors

Effective



The total capacitance is, therefore, more than that of any of the individual capacitors



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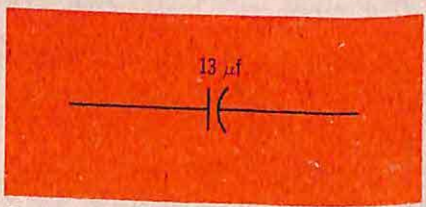


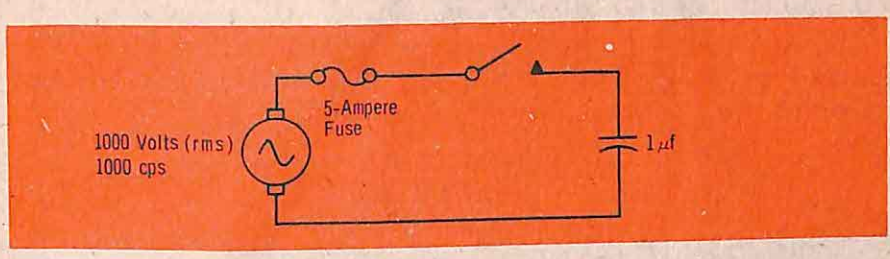
The total capacitance of parallel capacitors is equal to the sum of the capacitances of the individual capacitors:

$$C_{TOT} = C_1 + C_2 + C_3 + \ldots + \text{etc.}$$

The total capacitive reactance, though, is found by treating the individual reactances as parallel resistances:

$$X_{C\,TOT} = \frac{1}{\frac{1}{X_{C1}} + \frac{1}{X_{C2}} + \frac{1}{X_{C3}} + \ldots + \text{etc.}}$$

solved problems



Problem 8. Will the fuse in the circuit blow when the switch is closed?

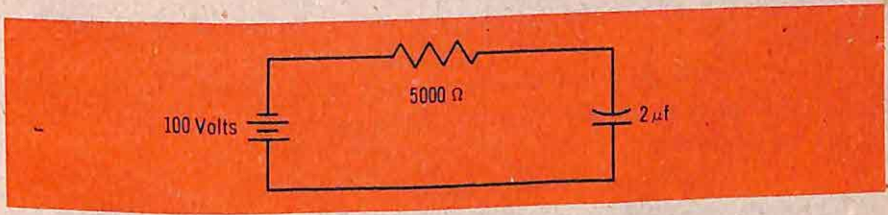
The fuse will blow if the current is greater than 5 amperes. Find the current with Ohm's Law after X_C is calculated.

$$X_C = \frac{1}{2\pi fc} = \frac{1}{(6.28 \times 1000 \times 0.000001)} = \frac{1}{0.00628} = 159 \text{ ohms}$$

Using Ohm's Law, then:

$$I = \frac{E}{X_C} = \frac{1000 \text{ volts}}{159 \text{ ohms}} = 6.3 \text{ amperes}$$

The fuse will therefore blow, since the current exceeds its rating.



Problem 9. How long will the current flow in the circuit?

Current will flow until the capacitor is fully charged, which will take 5 time constants. One time constant equals resistance times capacitance:

$$t = RC = 5000 \text{ ohms} \times 0.000002 \text{ farads} = 0.01 \text{ second}$$

Therefore,

$$5t = 5 \times 0.01 = 0.05 \text{ second}$$

Problem 10. If the voltage in the above circuit is increased to 200 volts, how long will the current flow?

With a higher voltage applied, the capacitor will charge to a higher voltage, but it will still do it in 0.05 second.

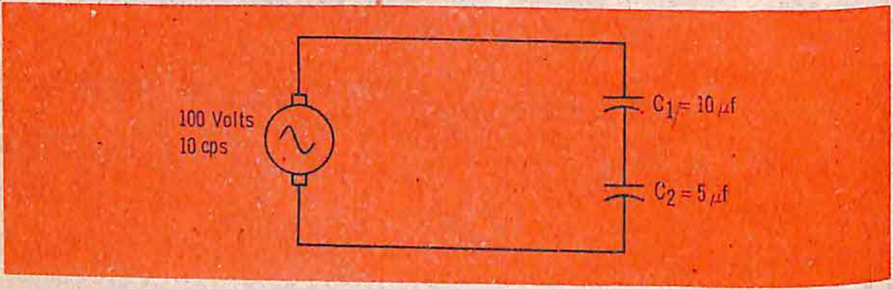
solved problems (cont.)

Problem 11. *What is the total capacitance of the circuit below?*

The capacitors are in series, so you use the same methods for finding the total resistance of parallel resistors. Since there are two unequal capacitors, the product/sum method is the best to use:

$$C_{TOT} = \frac{(C_1 \times C_2)}{(C_1 + C_2)} = \frac{(10\ \mu f \times 5\ \mu f)}{(10\ \mu f + 5\ \mu f)} = \frac{50\ \mu f}{15\ \mu f} = 3.33\ \mu f$$

Notice that it was not necessary to convert the values of the capacitors from microfarads to the farad. The reason for this is that only capacitance was involved in the problem, and all of the capacitances were in the same units.



Problem 12. *In the circuit, which capacitor has the most charge on its plates?*

Since current is the flow of charge, and at any instant is the same in all parts of a series circuit, both capacitors must have the identical charge at any instant.

Problem 13. *Which capacitor has the most voltage across it?*

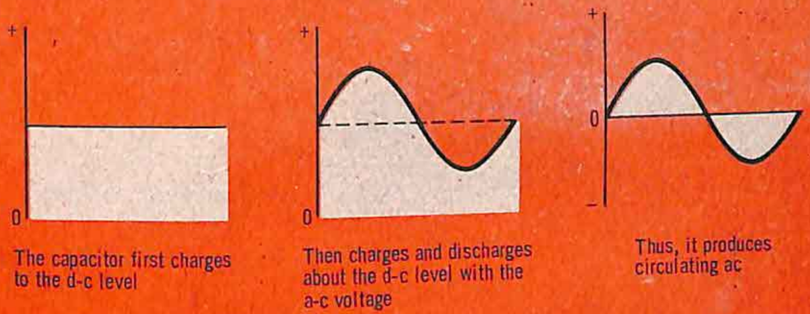
This problem could be solved by finding the capacitive reactance of the two capacitors, using it to calculate the total circuit current, and then using the current and the reactance of the individual capacitors to find the voltage drop across each. The easiest way to solve the problem is to rearrange the basic equation for capacitance, $C = Q/E$.

$$E = Q/C$$

And since you know that the charge (Q) on both capacitors is the same, this equation shows that the one with the smallest capacitance (C) must have the largest voltage (E) across it. This fact holds true whenever capacitors are connected in series. The one with the smallest capacitance always has the largest voltage across it. C_2, then will drop twice as much voltage as C_1.

capacitance in fluctuating d-c circuits

You learned that fluctuating dc has characteristics of both ac and dc. It consists of a component, the *a-c component*, which varies in amplitude but not direction, as well as another component, the *d-c reference*. The d-c reference is a value of dc around which the a-c component varies. When a fluctuating d-c voltage is applied to a capacitor, the capacitor charges almost instantly to the value of the d-c reference. It then charges further and discharges according to the a-c component. The capacitor never fully discharges, since it always maintains some charge as a result of the d-c reference. The maximum voltage across the capacitor is equal to the value of the d-c reference plus the peak value of the a-c component. The minimum voltage is equal to the d-c reference minus the peak value of the a-c component.



The capacitor first charges to the d-c level

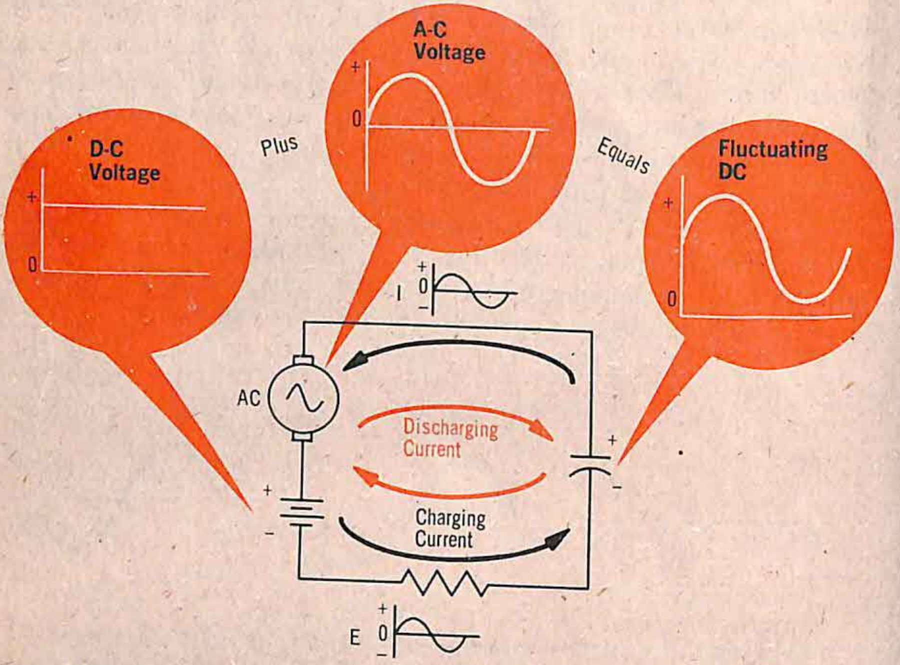
Then charges and discharges about the d-c level with the a-c voltage

Thus, it produces circulating ac

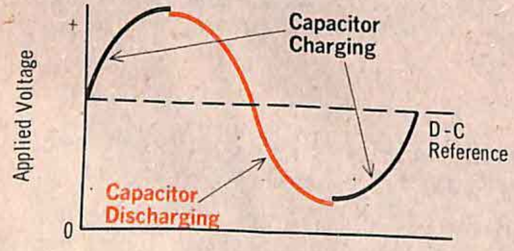
In effect, the capacitor charges to the d-c level and cancels it, so that only the a-c component is left to provide current flow

When the a-c component is *increasing*, the capacitor is *charging*, and the current flows in the corresponding direction. When the a-c component *decreases*, the capacitor *discharges partially*, and so the current *reverses* direction. Thus, although the applied voltage never changes direction, the circuit current does each time the capacitor starts to discharge. The circuit current, then, acts as if the applied voltage consisted only of the a-c component. In effect, the a-c component is *separated* from the d-c reference; an a-c current that varies around *zero* is produced. If a resistor were added in series with the capacitor, the a-c component would be dropped across it as voltage that varied around zero. Thus, the capacitor *blocks* the dc, and *passes* the *ac*.

capacitance in fluctuating d-c circuits (cont.)

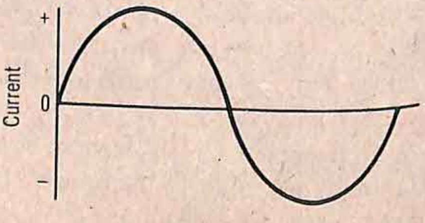


A fluctuating d-c voltage source varies in amplitude, but never reverses polarity. The current through a capacitor connected to such a source, though, does change direction



Capacitor charges when the applied voltage is increasing, and discharges when voltage is decreasing. Current, therefore, follows the a-c component

Current variations follow the a-c component, but are around zero instead of around the d-c reference. In effect, then, the capacitor separates the a-c component



summary

☐ In an a-c circuit, the voltage across a capacitor constantly changes polarity. ☐ A-c current is passed by a capacitor because the capacitor alternately charges and discharges during every cycle of the applied ac.

☐ The capacitor voltage is often called the counter voltage, because it acts 180 degrees out of phase with the applied voltage. ☐ The voltage across a capacitor lags the current through the capacitor by 90 degrees. Or, the current through a capacitor leads the applied voltage by 90 degrees. ☐ Current through a capacitor is directly proportional to the frequency of the applied voltage.

☐ The opposition offered to the flow of current by a capacitor in an a-c circuit is called capacitive reactance, and is abbreviated X_C. ☐ Capacitive reactance can be found by the equation: $X_C = 1/(2\pi fC)$. X_C is expressed in ohms. ☐ Leakage current in a capacitor is due to the leakage resistance, which is caused by the dielectric not being a perfect insulator. ☐ The total capacitance of capacitors in series is $C_{TOT} = \frac{1}{1/C_1 + 1/C_2 + 1/C_3 + \ldots + \text{etc.}}$. ☐ The total capacitance of capacitors in parallel is $C_{TOT} = C_1 + C_2 + C_3 + \ldots + \text{etc.}$ ☐ Capacitors in fluctuating d-c circuits block the dc while passing the ac.

review questions

1. How does a capacitor block dc?
2. What are the voltage and current relationships between the capacitor and applied voltages? Between the capacitor current and applied voltage?
3. What happens to the capacitor current if the frequency of the applied voltage is decreased?
4. What is the opposition to the flow of a-c current offered by a capacitor called? What are its units?
5. What is the equation for finding X_C?
6. What is meant by *leakage current* in a capacitor, and what causes it?
7. What is the total capacitance of three capacitors in series, whose values are 10, 10, and 5 microfarads?
8. What is X_C for each capacitor in Question 7, and the total capacitive reactance at 100 cps? 10 kc? 1 mc?
9. What is the total capacitance of three capacitors in parallel, whose values are 10, 10, and 5 microfarads.
10. What is X_C for each capacitor in Question 9, and the total capacitive reactance at 100 cps? 10 kc? 1 mc?

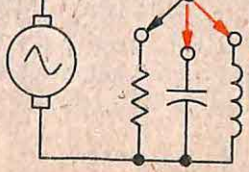
power factor

In d-c circuits, or purely resistive a-c circuits, the power consumed is equal to the voltage times the current, or P = EI. In circuits containing reactance, though, the relationship between voltage, current, and power consumed is not so simple. The reason for this is that much of the power drawn from the source by inductors and capacitors instead of being consumed, is *stored* temporarily, and then returned to the source. The power is stored in the magnetic field of inductors and the electrostatic field of capacitors. If you were to measure the voltage and current in an inductive or capacitive circuit and then multiply them together, you would obtain the *apparent power*. This is the power supplied to the circuit by the source, but is not the power consumed by the circuit, which is the *true power*. To convert apparent power to true power, you must multiply the apparent power by the *cosine* of the phase angle (θ) between the voltage and current in the circuit. Mathematically, this is expressed as:

$$\text{True power } (P) = EI \cos \theta$$

The value of cosine θ is called the *power factor* of the circuit. In a purely resistive circuit, the voltage and current are *in phase*, and so the phase angle between them is *zero*. Since the cosine of θ is 1, the apparent power *equals* the true power in resistive circuits. In a purely inductive or capacitive circuit, the phase angle between the voltage and current is 90 degrees. The cosine of 90 degrees is zero, and so the true power equals the apparent power times zero; the true power, then is zero. This means that no power is consumed in the circuit. All of the power drawn from the source is returned to it.

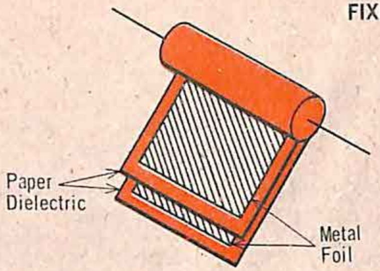
Actually, all circuits contain some resistance. In reactive circuits, the effect of resistance is to *reduce* the phase angle between the voltage and current. The cosine of the angle is no longer zero, and some of the power drawn from the load is consumed in the circuit resistance. The true power then depends on the relative amounts of resistance and reactance in the circuit. This is covered in detail with RL and RC circuits in Volume 4.

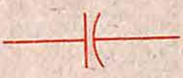


In a purely resistive circuit, the power factor equals 1.0, and so the apparent power equals the true power

In a purely inductive or capacitive circuit, the power factor equals 0, and so no power is consumed by the circuit

FIXED CAPACITOR



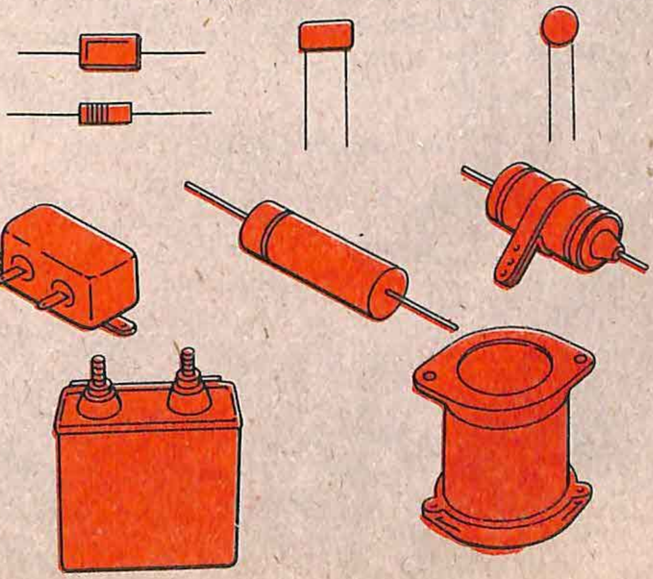


This is the Symbol For A Fixed Capacitor

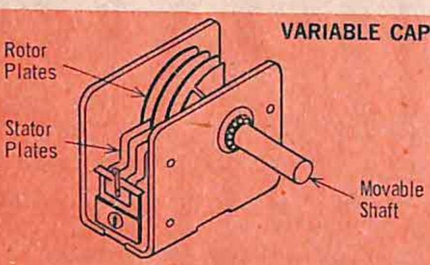
types of capacitors

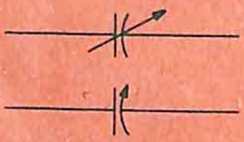
A wide variety of capacitor types is used today. Essentially, they fall into either of two broad categories: *fixed* capacitors, or *variable* capacitors. Fixed capacitors have their capacitance value *permanently* set by their construction, and this value cannot be changed. The most common get their names from the dielectric materials used. Examples of these are *paper* capacitors, *mica* capacitors, and *ceramic* capacitors. The plates of these capacitors are usually made of metal foil. To keep their physical size to a minimum, techniques such as the use of a series of plates separated by dielectric material, or the rolling of the plates and the dielectric material into a tubular shape, are used in the construction of fixed capacitors.

Typical Fixed Capacitors



VARIABLE CAPACITOR





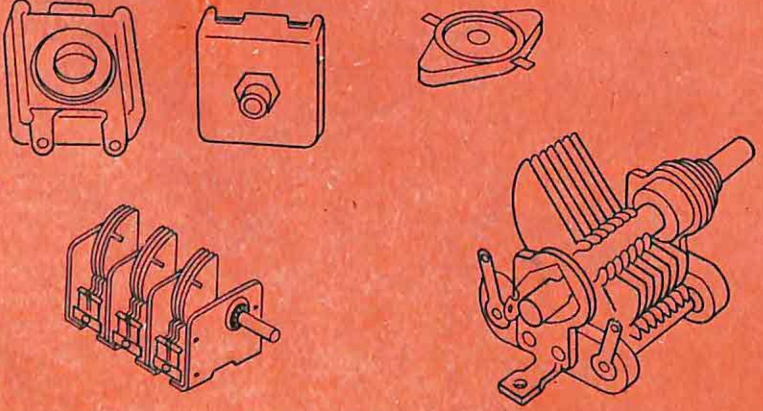
These are the Symbols For a Variable Capacitor

types of capacitors (cont.)

Variable capacitors are made so that their capacitance values can be *continuously adjusted* over a certain range. The most common type consists of two sets of interleaving metal plates. One set of these plates, the *rotor* plates, is mounted on a shaft, which when rotated, moves the plates in between the other set of plates, the *stator* plates. Effectively, one set of plates acts as one of the capacitor plates, and the other set as the other plate. The more the two sets of plates are interleaved, the greater is the effective *area* of the capacitor plates, and so the greater is the capacitance. Air serves as the dielectric between the plates. Another variable capacitor consists of two metal plates whose *separation* can be varied by a screw adjustment. Generally, mica is used between the plates of this type of variable capacitor.

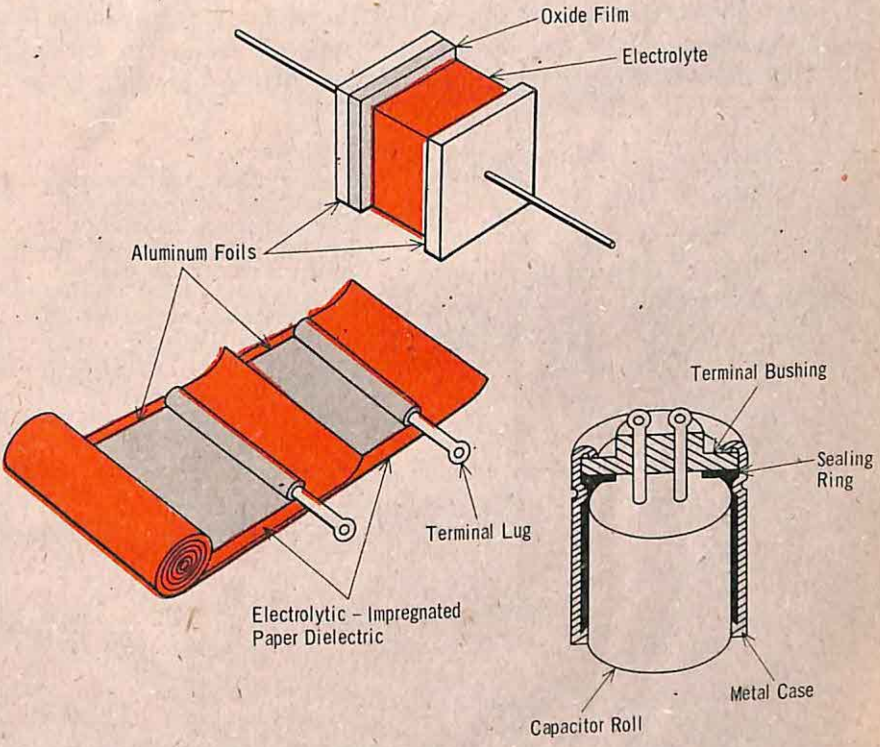
Most capacitors are marked with a d-c working voltage (WVDC), the *maximum* d-c voltage that can safely be applied across the capacitor. If this voltage is exceeded, breakdown of the dielectric might result, and the capacitor would become useless.

Typical Variable Capacitors



the electrolytic capacitor

The capacitors previously described are generally limited to values less than 1 μf because of size and cost considerations. For larger values, special capacitors, called *electrolytic capacitors*, are used. Capacitances as large as several thousand microfarads can be obtained with electrolytic capacitors at a reasonable size and cost. There are two basic types of construction used for electrolytic capacitors: the *wet type* and the *dry type*. The wet type is now practically obsolete, and so only the dry type will be described.

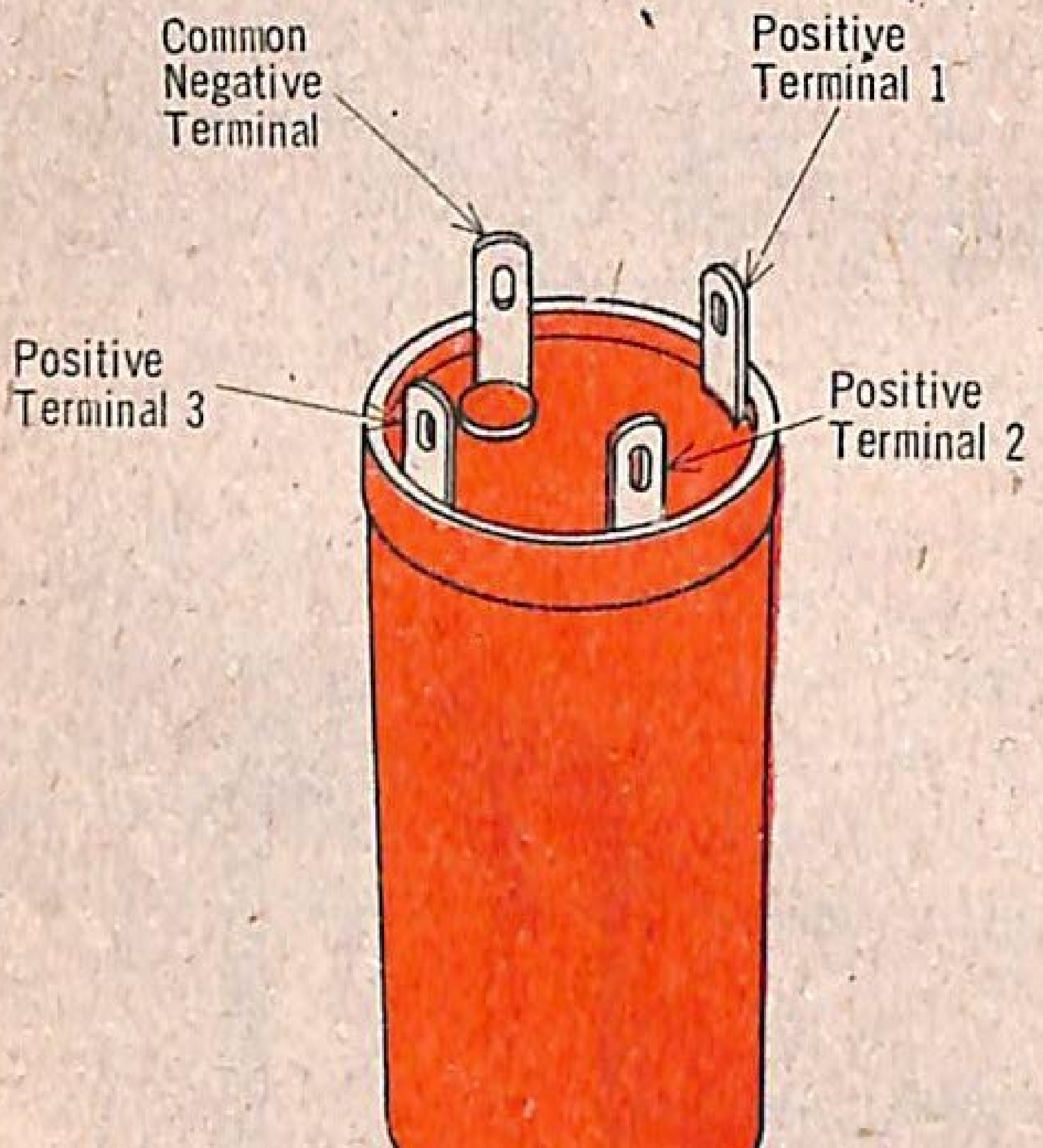


Essentially, a dry-type electrolytic capacitor consists of two aluminum sheets separated by a layer of paper saturated with a liquid chemical called the *electrolyte*. All three sheets are rolled together and sealed in a container. When the capacitor is first made, a d-c voltage is applied between the two aluminum sheets. The resulting current causes a thin *oxide layer* to be *formed* on one aluminum sheet, and as a result, the capacitor is *polarized*.

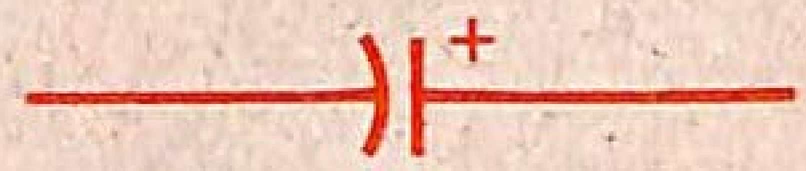
the electrolytic capacitor (cont.)

The aluminum sheet with the oxide layer is positive, and serves as the positive capacitor plate. The oxide layer has insulating properties, and serves as the dielectric for the capacitor. The electrolyte is the negative capacitor plate, and the second aluminum sheet merely provides a connection between the electrolyte and external circuits.

Since the electrolytic capacitor is polarized, it can only be used in circuits containing *fluctuating d-c voltages*. Furthermore, the positive and negative terminals of electrolytic capacitors must be connected to circuit points of the same polarity (negative to negative, and positive to positive). The reason for this is that the electrolytic capacitor acts as a capacitor in only one direction of applied voltage. In the other direction, the electrolytic capacitor conducts like a low-value resistor.



In the construction of electrolytic capacitors, it is common to place several positive plates in a single container. Then the electrolyte and a single negative plate serve for all the positive plates. In this way, two or three capacitors can be contained in a single unit



The symbol for an electrolytic capacitor shows polarity

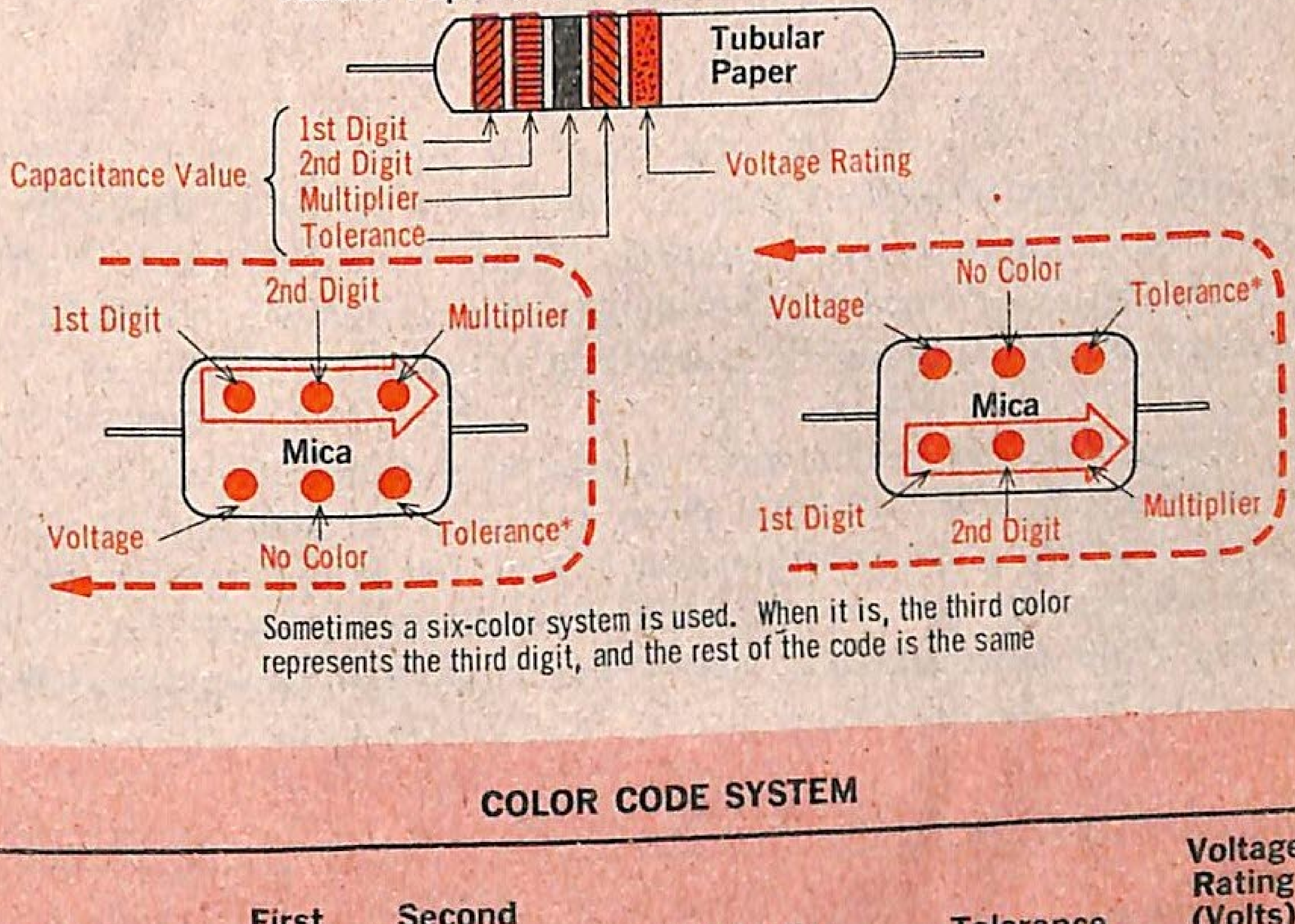
As a matter of fact, if an electrolytic capacitor is connected backwards, it could "explode" because of the high current that would flow. Special electrolytic capacitors are available for use in a-c circuits. In these capacitors, two positive plates are used, thus permitting a reversal in polarity of the applied voltage. Essentially, this type is made of two electrolytics connected back to back.

Wet-type electrolytic capacitors are similar in construction to the dry type. The principal difference is that they use liquid electrolytes. The electrolytic capacitor has a much lower leakage resistance than the regular capacitors.

capacitor color codes

All capacitors are marked in some way with their capacitance value. In addition, other important characteristics, such as working voltage and tolerance, are sometimes indicated. Where practical, this information is printed on the capacitor. In many cases, though, this is impractical, and a system of *colored markings* is used instead. The interpretation of these colored markings make up capacitor *color coding systems*. These are somewhat similar to the resistor color code system described in Volume 2. However, capacitor color codes are not too well standardized, so it would be wise to get the code from the specific manufacturers.

Five-Dot and Band Color Code System For Molded Tubular Paper and Mica Dielectric Capacitors



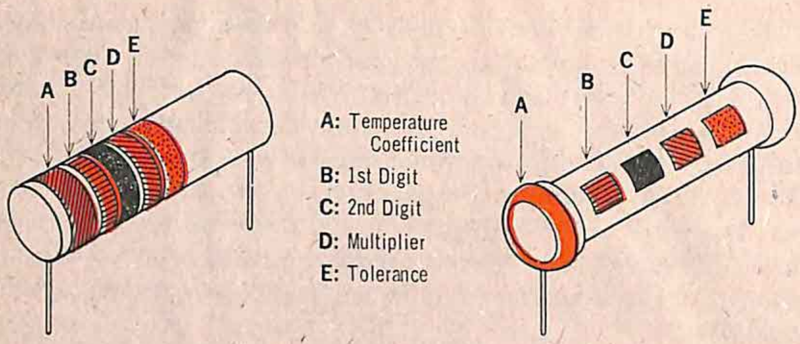
Sometimes a six-color system is used. When it is, the third color represents the third digit, and the rest of the code is the same

COLOR CODE SYSTEM

Color	First Digit	Second Digit	Multiplier	Tolerance	Voltage Rating (Volts)
Black	0	0	1	±20	100
Brown	1	1	10	±1	200
Red	2	2	100	±2	300
Orange	3	3	1000	±3**	400
Yellow	4	4	10,000	±4**	500
Green	5	5	100,000	±5	600
Blue	6	6	1,000,000	±6	700
Violet	7	7	10,000,000	±7	800
Gray	8	8	100,000,000	±8	900
White	9	9	1,000,000,000	±9	1000
Gold	—	—	0.1	±5	2000
Silver	—	—	0.01	±10	—

* No color for tolerance dot indicates tolerance of ±20%.
** Multiply by 10 for tubular paper capacitors.

Color Code System For Some Ceramic Capacitors



capacitor color codes (cont.)

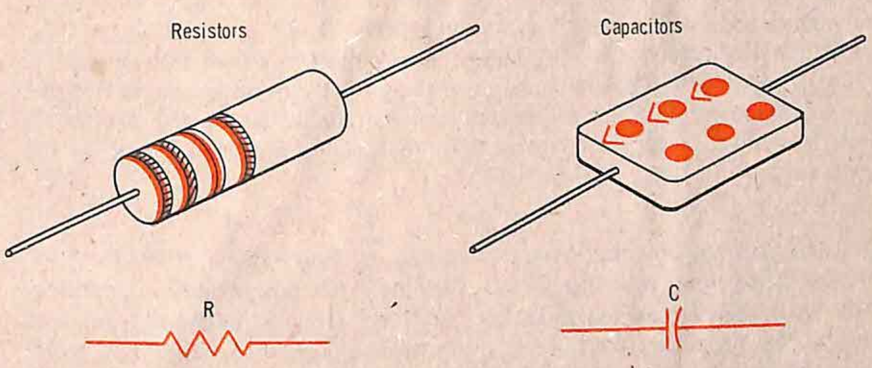
The temperature coefficient band is wider than the other bands for identification. Sometimes this band is last. When it is, though, the rest of the code remains the same. Also, the tolerance band can be left off. If six bands are used, there is a third digit. No tolerance band means 20%.

The temperature coefficient indicates the change in temperature in parts per million that will take place for every degree rise in the capacitor's operating temperature above 20°C. A minus means that capacitance will decrease, while a plus means that it will increase. These capacitors are all rated at 500 WVDC, unless otherwise indicated.

COLOR CODE SYSTEM

Color	First Digit	Second Digit	Multiplier	Tolerance More than 10 pf (%)	Tolerance Less than 10 pf (pf)	Temperature Coefficient
Black	0	0	1.0	±20	±2	0
Brown	1	1	10	±1	—	−30
Red	2	2	100	±2	—	−80
Orange	3	3	1000	±3	—	−150
Yellow	4	4	10,000	±4	—	−220
Green	5	5	—	±5	±0.5	−330
Blue	6	6	—	±6	—	−470
Violet	7	7	—	±7	—	−750
Gray	8	8	0.01	±8	±0.25	+30
White	9	9	0.1	±10	±1	+120 to −750
Gold	—	—	0.1	±5	—	—
Silver	—	—	0.01	±10	—	—

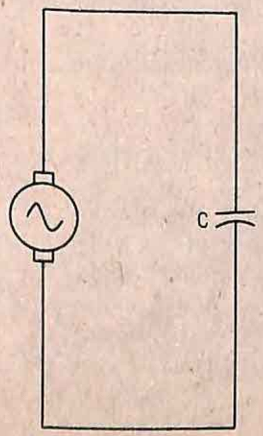
RC Circuits Contain



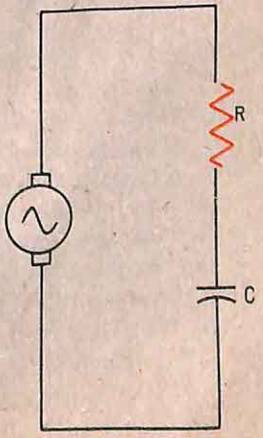
RC circuits

Capacitors and capacitance have been described so far from the standpoint of their effects on circuits that contain *no resistance*. As you know, though, every circuit contains some resistance, even if it is only the resistance of the circuit wiring and the internal resistance of the source. When the circuit resistance is very low compared to the capacitive reactance, the resistance can usually be ignored, as has been done in this volume. However, when the resistance becomes appreciable, it must be considered.

Circuits that contain both resistance (R) and capacitance (C) are called *RC circuits*. The relationships between resistance and capacitance in RC circuits and their joint effect on circuit operation are covered in Volume 4.



No circuit contains only capacitance, since the power source has some internal resistance as does the circuit wiring. This resistance is usually represented as a resistor in series with the capacitance. If the value of the resistance is significant, an RC circuit is formed.



summary

☐ The power factor of a circuit is the cosine of the phase angle (θ) between the voltage and the current. It can vary between 0 and 1, depending on the circuit. ☐ The actual power consumed in a circuit is called true power. ☐ Apparent power is the power supplied to the circuit by the source. It is equal to the voltage of the source times the current delivered by the source. ☐ True power in a circuit can be found by multiplying apparent power by the power factor.

☐ Capacitors can be either fixed or variable. ☐ Some types of fixed capacitors are paper, mica, and ceramic. ☐ Variable capacitors include the rotating-plate type, with air as the dielectric; and the screw-adjustment type, with mica as the dielectric. ☐ The maximum d-c voltage a capacitor can safely withstand is abbreviated WVDC.

☐ The electrolytic capacitor is polarized, and must be inserted in a circuit with the proper polarity. Special electrolytic capacitors, with high values of capacitance, are available for use in a-c circuits. ☐ Capacitor color codes permit identification of important characteristics. These characteristics include capacitance value, tolerance, voltage rating, and temperature coefficient.

review questions

1. What is meant by the *power factor* of a circuit?
2. The apparent power in a circuit is 50 volt-amperes, and the true power is 40 watts. What is the power factor?
3. Why are paper, mica, and ceramic capacitors so called? Are these fixed or variable capacitors?
4. What is meant by the abbreviation *WVDC* that is found on a capacitor?
5. What is an *electrolytic capacitor*? Can it ever be used in an a-c circuit?
6. How are capacitors identified?
7. What is meant by *rotor* and *stator plates*? Do fixed capacitors have these?
8. Why are the polarities of electrolytic capacitors important? Can these capacitors always be used for dc? For ac?
9. The power factor of a circuit is 0.5. What is the phase angle between the voltage and current?
10. What is the power factor in a pure capacitive circuit? Resistive circuit?

index

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